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Deep-retrofit decision-making support for achieving nearly zero-energy buildings with enhanced comfort

Sheikh Zuhaib

Supervisor:
Dr. Jamie Goggins

Co-supervisors:
Dr. Marcus M. Keane & Dr. Magdalena Hajdukiewicz

A thesis submitted to the National University of Ireland as fulfilment of the requirements for the Degree of Doctor of Philosophy.

Civil Engineering,

National University of Ireland, Galway.
April 2019
Dedicated to:

the love of my life....my beloved wife.
Declaration

This thesis or any part thereof, has not been, or is not currently being submitted for any degree at any other university.

Sheikh Zuhaib

Date: 08.04.2019

The work reported herein is as a result of my own investigation, except where acknowledged and referenced.

Sheikh Zuhaib

Date: 08.04.2019
Abstract

The emerging trends for deep-retrofit of existing buildings in Europe require formulation of strategies for nearly zero-energy buildings (nZEBs) and achieving benchmarks as outlined in the Energy Performance of Buildings Directive (EPBD) recast. The fundamental process of retrofitting to an explicit high performance (both energy and comfort) necessitates the development of robust and diverse methodologies to be used during the early-stages of planning in retrofit projects. The construction sector lacks the extensive use of such methods for early decision-making that are essential to accelerate building renovation in Europe. Therefore, considering the need to upgrade existing buildings to nZEB, the thesis aims at developing decision-making support for deep-retrofits. This research presents the application of combined (i) research techniques, (ii) audit and assessment methods, (iii) building simulation, and (iv) optimisation strategies investigated on an existing building field-study that shall support the decision-making in retrofitting existing buildings to low-energy and comfortable buildings. The overall research methodology incorporated a preliminary scoping study, including literature review and stakeholder analysis, followed by a detailed field-study, building simulation and optimisation for deep-retrofit analysis and solutions.

The scoping study was designed to assess the gaps in theory through literature review and practice using surveys, a workshop and focused interviews investigating experience, knowledge, expectation, and needs of retrofit industry stakeholders in Ireland. The results of this scoping study informed the overall methodology for research in this thesis. A systematic field-study was conducted on a partially-retrofitted university building (built during 1970s) in Ireland. The different building performance metrics for energy and comfort were examined for the existing building and their optimisation opportunities were identified. Furthermore, an indoor environmental quality (IEQ) assessment was carried out using standards-based procedures and practices along with detailed energy audits and occupant surveys. The metrics of thermal, visual and acoustic comfort, together with indoor air quality (IAQ), were analysed for occupant satisfaction. This formed the basis for further investigation focusing on achieving nearly zero-energy performance with improved IEQ and led to the identification of proposed retrofit measures.
The further investigation involved the development of a whole-building energy simulation models using the field-study data. A novel multi-stage automated-calibration methodology was developed to calibrate the simulation model using genetic algorithm (GA). The methodology combined a rigorous uncertainty analysis of simulation input parameters using the Morris method. The model was calibrated and validated with the energy and environmental reference datasets from the field-study meeting the acceptance criteria outlined in the standards.

Furthermore, the impact of several proposed retrofit measures on energy, comfort, and cost were evaluated using the calibrated model, through multi-objective optimisation (MOO) (Pareto fronts), to explore deep-retrofit solution packages. The main objectives of the MOO were primary energy consumption (PEC), discomfort hours (DH) and net present value (NPV) of life cycle-costs (LCC). An additional analysis of IAQ was also conducted, which provided added benefits that were also taken into consideration in the proposed deep-retrofit solution packages. To validate the effectiveness of these solutions, single-step and staged-retrofit approaches were examined for their feasibility in achieving cost-optimal nZEB performance.

The overall work concludes with different retrofit approaches for critical assessment tied to the main research methodology that supports the decision-making for non-domestic retrofits from the energy, cost and IEQ perspective. Multi-objective optimisation ensured robust model calibration and analysis of most optimal solutions for the decision-making of deep-retrofit packages based on selected objectives. Findings of this research may (i) benefit the non-domestic deep-retrofit projects (and their stakeholders) to develop a systematic approach and processes to achieve nZEBs, (ii) provide evidence that deep-retrofit of non-domestic buildings can significantly reduce their energy consumption, (iii) strengthen and align the focus of retrofit industry on improving IEQ together with energy efficiency, (iii) inform the local legislation into setting up the nZEB benchmarks for existing buildings performance and, (iv) add to the primary case study database on non-domestic buildings outlining the deep-retrofit impact.
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I would like to express my sincere gratitude towards my supervisor Dr. Jamie Goggins for his persistent support, patience, inspiration, and immense knowledge-sharing throughout my PhD tenure. I could not have imagined having a better advisor and mentor. I would also like to thank my co-supervisors Dr. Magdalena Hajdukiewicz and Dr. Marcus M. Keane for their insightful comments and encouragement, as well as their constructive critiques that incented me to widen and strengthen research perspectives.

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Last but not the least, I thank all my colleagues and friends at work for the stimulating discussions and environment, and for all the good times we had in the last four years at the University.
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<tbody>
<tr>
<td>ACH</td>
<td>Air changes per hour</td>
</tr>
<tr>
<td>ASHRAE</td>
<td>America Society of Heating, Refrigerating and Air-Conditioning Engineers</td>
</tr>
<tr>
<td>BEM</td>
<td>Building Energy Modelling</td>
</tr>
<tr>
<td>BER</td>
<td>Building Energy Rating</td>
</tr>
<tr>
<td>BPIE</td>
<td>Building Performance Institute Europe</td>
</tr>
<tr>
<td>BPS</td>
<td>Building Performance Simulation</td>
</tr>
<tr>
<td>BRE</td>
<td>Building Research Establishment</td>
</tr>
<tr>
<td>BRP</td>
<td>Building Renovation Passport</td>
</tr>
<tr>
<td>CBE</td>
<td>Centre for Built-Environment</td>
</tr>
<tr>
<td>CIE</td>
<td>Commission Internationale de l’Eclairage</td>
</tr>
<tr>
<td>CPC</td>
<td>Carbon Performance Coefficient</td>
</tr>
<tr>
<td>CvRMSE</td>
<td>Coefficient of variation of the Root Mean Square Error</td>
</tr>
<tr>
<td>DCENR</td>
<td>Department of Communications, Energy and Natural Resources</td>
</tr>
<tr>
<td>DECLG</td>
<td>Department of the Environment, Community and Local Government</td>
</tr>
<tr>
<td>DGI</td>
<td>Daylight Glare Index</td>
</tr>
<tr>
<td>DH</td>
<td>Discomfort Hours</td>
</tr>
<tr>
<td>DoE</td>
<td>Department of Energy</td>
</tr>
<tr>
<td>EBC</td>
<td>Energy in Buildings and Communities Programme</td>
</tr>
<tr>
<td>EED</td>
<td>Energy Efficiency Directive</td>
</tr>
<tr>
<td>EPBD</td>
<td>European Directive on Energy Performance of Buildings</td>
</tr>
<tr>
<td>EPC</td>
<td>Energy Performance Coefficient</td>
</tr>
<tr>
<td>ESCO</td>
<td>Energy Service Company</td>
</tr>
<tr>
<td>EU</td>
<td>European Union</td>
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<tr>
<td>FEC</td>
<td>Final Energy Consumption</td>
</tr>
<tr>
<td>GA</td>
<td>Genetic algorithm</td>
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<tr>
<td>GBPN</td>
<td>Global Building Performance Network</td>
</tr>
<tr>
<td>GWP</td>
<td>Global Warming Potential</td>
</tr>
<tr>
<td>HVAC</td>
<td>Heat, Ventilation and Air-conditioning</td>
</tr>
<tr>
<td>IAQ</td>
<td>Indoor Air Quality</td>
</tr>
<tr>
<td>ICT</td>
<td>Information Communication Technologies</td>
</tr>
<tr>
<td>IEQ</td>
<td>Indoor Environmental Quality</td>
</tr>
<tr>
<td>IMPVP</td>
<td>International Performance Measurement and Verification Protocol</td>
</tr>
<tr>
<td>ISO</td>
<td>International Standards Organisation</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
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<td>---------</td>
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</tr>
<tr>
<td>LCC</td>
<td>Life-Cycle Cost</td>
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<tr>
<td>MOO</td>
<td>Multi-objective optimisation</td>
</tr>
<tr>
<td>MVHR</td>
<td>Mechanical Ventilation with Heat Recovery</td>
</tr>
<tr>
<td>N DFA</td>
<td>National Development and Finance Agency</td>
</tr>
<tr>
<td>NEEAP</td>
<td>National Energy Efficiency Action Plan</td>
</tr>
<tr>
<td>NGO</td>
<td>Non-governmental organisation</td>
</tr>
<tr>
<td>NM BE</td>
<td>Normalised Mean Bias Error</td>
</tr>
<tr>
<td>NP V</td>
<td>Net Present Value</td>
</tr>
<tr>
<td>NSGA</td>
<td>Non-dominated Sorting Genetic Algorithm</td>
</tr>
<tr>
<td>n ZEB</td>
<td>nearly Zero-Energy Building</td>
</tr>
<tr>
<td>OECD</td>
<td>Organisation for Economic Co-operation and Development</td>
</tr>
<tr>
<td>PEC</td>
<td>Primary Energy Consumption</td>
</tr>
<tr>
<td>PM V</td>
<td>Predicted Mean Vote</td>
</tr>
<tr>
<td>PPD</td>
<td>Predicted Percentage Dissatisfied</td>
</tr>
<tr>
<td>PV</td>
<td>Photovoltaic</td>
</tr>
<tr>
<td>REHVA</td>
<td>Federation of European Heating, Ventilation and Air Conditioning Associations</td>
</tr>
<tr>
<td>RMSD</td>
<td>Root Mean Square Deviation</td>
</tr>
<tr>
<td>SBS</td>
<td>Sick Building Syndrome</td>
</tr>
<tr>
<td>s DA</td>
<td>Spatial Daylight Autonomy</td>
</tr>
<tr>
<td>SEAI</td>
<td>Sustainable Energy Authority of Ireland</td>
</tr>
<tr>
<td>SME</td>
<td>Small and medium-sized enterprises</td>
</tr>
<tr>
<td>TR V</td>
<td>Thermostatic Radiator Valve</td>
</tr>
<tr>
<td>TSV</td>
<td>Thermal Sensation Vote</td>
</tr>
<tr>
<td>U DI</td>
<td>Useful Daylight Illuminance</td>
</tr>
<tr>
<td>VOCs</td>
<td>Volatile Organic Compounds</td>
</tr>
<tr>
<td>WBCSD</td>
<td>World Business Council for Sustainable Development</td>
</tr>
<tr>
<td>WHO</td>
<td>World Health Organisation</td>
</tr>
<tr>
<td>WLC</td>
<td>Whole Life Cost</td>
</tr>
<tr>
<td>WWR</td>
<td>Window-wall ratio</td>
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List of Publications

The work contained in this thesis consists of the following publications in international peer reviewed journals:

Chapter 3:

Chapter 4:

Chapter 5:

Chapter 6:

Note: Sheikh Zuhaib is the primary author for each journal publication.
Chapter 1 : Introduction
Chapter 1. Introduction

1.1 Chapter overview

Over the last decades, the European Union (EU) recognised significant contribution of the building sector to total final energy consumption [1] and introduced a number of energy efficiency regulatory mechanisms for both new and existing buildings. These mechanisms included the European Directive 2002/91/EC on the Energy Performance of Buildings (EPBD) [2], the EPBD recast (Directive 2010/31/EC) [3] and the Energy Efficiency Directive (EED) [4]. These directives aim at improving the energy efficiency of the building stock and promoting efficient renovation. Buildings are the largest energy-consuming sector in the EU, accounting for nearly 40% of the total energy consumption and 36% of the total CO$_2$ emissions in the EU [5]. Thus, for the EU to achieve the ambition of decarbonising its economy [6], an energy efficient low-carbon building stock is required. In this regard, strong focus is being given to the long-term renovation strategies for buildings (15-20 years) to ensure the goal of achieving low-energy buildings and decarbonise the building stock by 2050 [6]. The main purpose of improving the energy efficiency of buildings is to generate social, economic and environmental benefits. Most of these energy efficiency regulations have been issued for new buildings. However, in more recent years there has been an increased focus by the EU [7] on making existing buildings healthier that protect occupant health and improve wellbeing [8] with low-energy consumption. There is a rising demand in the renovation market across the EU for cost-effective retrofitting technologies and solutions.

This research addresses the underlying challenges of decision-making in the process of achieving nearly zero-energy buildings (nZEBs) with a focus on retrofitting existing buildings. The current retrofit industry in the EU is fragmented and lacks integrated supply chains, standardised methods and approaches, technologies and tools to make decisions based on energy savings, cost-optimality and payback in the retrofit projects [9]. Despite the fact that the EU construction industry has been developing over the past few years, the rate of renovation of existing buildings is quite low [10]. To understand the existing problems of the retrofit industry in Ireland and deliver focused results, this research carried out an initial scoping study. The scoping study contains both a literature review and stakeholder engagement and it is presented in detail in Chapters 2 and 3, respectively. This research attempts to outline the process of achieving nearly-zero energy performance through a field-study of an existing university building that was partially retrofitted. The on-site measurements were taken over a two year period and extensive building energy modelling is utilised.
Chapter 1. Introduction

This chapter presents the background that forms the motivation for this thesis. The current legislation and practice in EU with respect to energy efficiency is presented. Sections of this chapter focus on outlining the trends and insights into the energy consumption of EU member states. Future energy consumption targets are also presented as estimated by the European Commission for the energy efficiency of buildings. A pattern of final energy consumption of different sectors other than buildings (e.g., transport, industry and agriculture) and their comparison is also given. A brief review of policies on energy efficiency is presented, along with the status of nZEB’s policies within the EU outlining the national definitions of member states. Finally, the research framework and scientific relevance is presented for this thesis.

1.2 Energy consumption by sector in the EU

An overview of the final energy consumption of all the sectors in the EU is outlined in this section to estimate the impact achieved through energy efficiency of buildings. Between 2005 and 2014, the final energy consumption of EU-28 countries witnessed a considerable decrease by 11% with a 1.3% rate annually [11]. There was a 26.5% decrease in final energy consumption across the EU-28 countries attributed to buildings, which accounted for 25.7% of overall reduction in final energy consumption across all sectors. The contribution of final energy consumption for each sector in European member states (in 2015) is shown in Figure 1.1. It is estimated that the major contribution to energy reduction can be attributed to the two sectors namely Industry and Households by decreasing the final energy consumption by 13.6% [11].

Building energy consumption, industrial processes, agriculture, and transportation comprise the majority of overall energy consumption in EU (see Figure 1.1). In majority of EU member states, transportation is the largest energy consumer; except Germany, Sweden, Slovakia, Belgium and Czech Republic where the industry is a dominant energy consumer, and Hungary, Latvia, Estonia, where the residential sector consumes the most energy [12].
The largest decrease in final energy consumption was experienced by Greece (26%) and Spain (19%). Other countries with significant decrease were Hungary (18%), Portugal (17%), Italy (17%), Ireland (15%) and UK (15%) during 2005-14 [12]. The decrease in final energy consumption in Ireland and UK is partly a direct result of energy saving initiatives, whereas for Greece, Spain, Hungary, Portugal and Italy it was mainly as a result of decrease in economic activity [12]. Electricity consumption have been stable in the household sector since 2005, which is due to the balance between the increase in number of dwellings and increase in the use of energy efficient appliances and technologies [11].

Focusing the perspective on the building sector, within the EU, it is responsible for nearly 40% of the final energy consumption and contributes to nearly 36% of the carbon emissions [5]. 2013 calculated energy use intensity data for non-residential buildings (Figure 1.2) depicts that countries such as Italy, Malta, Estonia and Slovenia have energy use intensity above 380 kWh/m² compared to 184 kWh/m² for Ireland and 250 kWh/m² for average EU-28. For residential buildings, countries such as Belgium, Estonia, Romania and Latvia represent energy use intensity above 230 kWh/m², compared to 163 kWh/m² in Ireland and 183 kWh/m² for average EU-28. According to the EU building database [13], 35% of the building stock is more than 50 years old.
EU-28 countries are required to efficiently utilise energy from its production to final consumption under the Energy Efficiency Directive (EED) [4]. The EED established certain measures so that each EU member state can achieve a target of 20% improvement in energy efficiency by 2020. However, data from 2017 on these targets indicate that EU member states have established their own national energy efficiency targets to reach this goal. An overview of these targets for EU member states is given in Figure 1.3 based on primary energy consumption.

As can be seen in Figure 1.3, in 2015 some countries such as Denmark, Bulgaria, Slovakia, Ireland, Croatia, Slovenia, Estonia, Lithuania, Latvia, Luxembourg, Cyprus and Malta were below their primary energy consumption targets defined for 2020. Member states have also submitted their NEEAPs (National Energy Efficiency Action Plans) in 2017, outlining these targets for primary energy and final energy consumption, as well as their efforts to meet the targets that indicate slow progress [15].

![Figure 1.2 Calculated energy use intensity (kWh/m²) for EU building stock- 2013 [13]](image-url)
Moreover, the main findings of a report by the European Commission [15] show that energy consumption had gradually decreased between 2007-2014, but it increased in 2015, mainly due to cold winters and lower fuel prices [15]. It was found that the primary energy consumption increased by 1.5% compared to 2014 and it was still behind the 2020 target. Energy consumption has increased further from 2016, following fewer warm winters.

To further compare, Figure 1.4 shows that the total sum of the national 2020 targets from all EU member states for their primary energy consumption (PEC) falls short of an overall defined target for the EU (i.e. 16.9% reduction compared to a 20% target). Also, the target reduction in the final energy consumption (FEC) for all member states combined together is 19.6%, which falls slightly short of the 20% target for the whole of the EU set by EED.
Chapter 1. Introduction

Figure 1.4 EU energy efficiency targets for 2020 [16]

The findings of the report highlighted that achieving the national targets would be insufficient to reach the EU target for final energy consumption, as many member states have revised their targets in 2017 leading to higher uncertainty in their progress [15].

1.3 EU policies on energy efficiency for buildings

In the last decade, certain policies have been put in place by the EU to achieve the energy efficiency targets. There are three key directives that regulate the energy sector and related policies for energy efficiency of buildings [17].


The main legislative instruments of the EU are the directives of EPBD (2010) and EED (2012) that are responsible for the improvement in the energy efficiency of buildings. The EED has established binding measures to help EU reach its 20% energy efficiency target by 2020 [4], and with the recent update in 2016, the new target is set for 30% by 2030 [19]. The EPBD has
resulted in improvement of energy efficiency of buildings in EU member states exercised through national policies and regulations.

The European Parliament revised the EPBD in 2018 with a strong focus on cost-effective renovation of existing buildings with more energy efficient systems, and strengthening the energy performance of new buildings by making them smarter using information communication technologies (ICT) and electronic systems for operation [7]. Member states must incorporate this directive in their national laws by March 2020. Based on the requirements of achieving cost-effective nZEB for existing buildings, the member states are required to prepare long-term renovation strategies for both domestic and non-domestic buildings. Deep renovation and staged deep renovation are highlighted through preparing Building Renovation Passports (long-term renovation roadmap 15-20 years) [6]. One of the main aims of revised EPBD is the decarbonisation of building stock by 2050, ensuring a clear path to the low and zero-emission building stock [20].

A number of measures have also been adopted in the EU to reduce the energy consumption through different sectors [21] including:

- an annual reduction in national energy sales by 1.5%,
- accelerating the renovation of at least 3% (per year) of buildings that are owned and occupied by the central governments of member states compared to a current value across all the building stock in the EU of between 0.4-1.2% [22],
- setting energy efficiency standards and labelling of products that consume energy,
- use of smart meters for electricity and gas by 2020,
- providing easy access to consumption data to the consumers.

Over the last few years, member states have been in the process of updating (or have updated) their building regulations and National Energy Efficiency Action Plans (NEEAPs) as required by the EU Directives.

### 1.4 Building stock characteristics of the EU

The EU has made tremendous efforts to improve the energy efficiency of buildings via various regulatory mechanisms such as EPBD and EED, as discussed in previous sections. The performance of new buildings with innovative solutions have improved with time; however,
the performance of existing building stock remains poorly addressed. As a matter of fact, about 75% of the building stock is energy inefficient (assuming buildings built before 1990, which were not retrofitted, are not energy efficient). These buildings require renovation to enhance their standards in terms of energy efficiency and indoor comfort conditions [5]. The EU building stock reflects large variations in sectoral distribution, but residential buildings represent approximately 76% of total floor area in EU-28 buildings (see Figure 1.5), where lies a great potential to improve energy efficiency [13]. As per the data from 2013, the breakdown of non-residential buildings indicates that private and public offices represent 30% of the total area of non-residential buildings, wholesale properties cover up to 27% and educational establishments cover around 16% in EU-28 [13].

In 2017, a new database was launched for the EU building stock and its energy performance called ‘EU Building Stock Observatory’ [23]. The main purpose of this Observatory is to monitor: (1) energy efficiency levels of EU countries, (2) building certification schemes, (3) financing for renovation, and (4) energy poverty levels in the EU [17].

![Figure 1.5 Share of non-residential and residential building stock in total stock area in EU countries-2013](image)

*Figure 1.5 Share of non-residential and residential building stock in total stock area in EU countries-2013 [13]*
1.5 Renovation scenario in the EU

The rate of construction of new buildings is very low and approximately 0.4-1.2% of the existing building stock area is renovated per year in different EU countries [10]. Thus, existing large EU building stock possess significant potential for energy savings that can be achieved through innovative retrofitting strategies towards achieving higher renovation rates. It is expected that renovation of existing buildings could reduce the energy consumption of the EU by 5-6% [24]. To ensure that EU member states constantly make efforts to improve their national legislation on renovation, the European Directives have made specific provisions (Table 1.1).

<table>
<thead>
<tr>
<th><strong>Table 1.1 Provisions in European Directives for renovation</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Article 7: When buildings undergo major renovation, the energy performance of the building or the renovated part thereof needs to be upgraded in order to meet minimum energy performance requirements in so far as this is technically, functionally and economically feasible.</td>
</tr>
<tr>
<td>‘major renovation’ means the renovation of a building where:</td>
</tr>
<tr>
<td>(a) the total cost of the renovation relating to the building envelope or the technical building systems is higher than 25 % of the value of the building, excluding the value of the land upon which the building is situated; or</td>
</tr>
<tr>
<td>(b) more than 25 % of the surface of the building envelope undergoes renovation;</td>
</tr>
<tr>
<td>Article 4: Member States shall establish a long-term strategy for mobilising investment in the renovation of the national stock of residential and commercial buildings, both public and private</td>
</tr>
<tr>
<td>Article 5: Obligation for a renovation quota of 3% of all public buildings owned and occupied by central governments.</td>
</tr>
<tr>
<td>Member States should introduce measures to increase the share of energy from renewable sources in new and renovated buildings</td>
</tr>
<tr>
<td>Article 2a: Each Member State shall establish a long-term renovation strategy to support the renovation of the national stock of residential and non-residential buildings, both public and private, into a highly energy efficient and decarbonised building stock by 2050, facilitating the cost-effective transformation of existing buildings into nearly zero-energy buildings.</td>
</tr>
</tbody>
</table>
Current renovation scenario in the EU needs to be scaled up from approximately 1% of the total floor area rate to 3% from 2020 onwards so that the existing building sector can become energy efficient by 2050 [25]. Article 5 of the Energy Efficiency Directive stipulated in 2014 that all member states should ensure that 3% of the total floor area of the public owned buildings should be renovated each year to meet the energy performance requirements [4], [26].

Furthermore, the EPDB recast (2010/31/EU) [3] requires buildings that undergo major upgrades to meet the minimum energy performance requirements and are technically, functionally and economically feasible. This will be discussed in more detail in the next sections. Most of the retrofit activities generally achieve 20-30% of energy savings; however, deep-retrofits need to reach 60% of energy savings to reach full environmental and economic potential [27].

1.6 Nearly zero-energy buildings (nZEBs)

A nZEB is defined as a building that has very high energy performance with nearly zero or a very low amount of energy required. The low energy that this type of a building requires is covered to a very significant extent by energy from renewable sources [2].

1.6.1 nZEBs in the EU

The promotion of higher market uptake of nZEBs for both new and existing buildings depends on the national definitions across EU member states. In many countries the performance of a nZEB is indicated by the maximum primary energy consumption. This is based on a non-dimensional coefficient derived from the comparison of the primary energy use with a ‘reference’ building of a similar genre [28]. There is an urgent need to develop comprehensive nZEB regulations for existing buildings, whereas most of the mandatory requirements are already in place by the EU nations for new construction [29]. As reported by Zimmerman [30], 80% of the total energy consumption would be influenced by the existing building stock in most industrialised nations. Moreover, almost 70-90% of the current building stock will still be standing in 2050 in OECD (Organisation for Economic Co-operation and Development) countries [14].

Retrofits are challenging, as they may not yield higher energy performance with existing solutions without an integrated approach and adequate depth. Thus, it is significant to pose
serious questions to the retrofit process of the existing buildings. There are additional social, economic and environmental benefits of retrofitting buildings along with observable positive effects on health, productivity and indoor environmental quality. According to the Global Building Performance Network (GBPN), deep retrofits are the renovation practices that reduce the energy consumption of buildings post-retrofit by 75% and the consumption of energy required for heating, cooling, hot-water, lighting and ventilation is less than 60 kWh/m²/yr. [31]. Between 20-60% of the energy consumed by buildings is affected by their design and construction during retrofits [32].

Traditional building design has been quite distinct with a sequential set of activities. At initial stages, designers used rules of thumb to design buildings and verify their compliance to performance goals by modelling them at later stages. However, the nZEB targets have pushed architects and engineers to adopt performance-based decision tools during the early stages of design [33]. A good nZEB design is indistinctly related to the local scale, climatic factors, available technologies, materials and lifestyle of the population. The architectural design process for new construction, renovation or retrofit involves significant choices that will affect the energy performance of a building, mainly associated with envelope design [34]. Six main nZEB design aspects listed by Attia et al. [33] are i) comfort levels, ii) climate, iii) passive strategies, iv) energy efficiency, v) renewable systems, and vi) innovative solutions and technologies. nZEB performance requires primary energy reduction to near zero level, but the role and impact of retrofits on occupant’s satisfaction and comfort should not be neglected in order to meet the stringent targets of EU legislation. The new nZEB policies introduced by the EU have provided a huge opportunity for improving indoor environmental quality (IEQ) of the existing buildings; thus affecting the health, well-being and productivity of occupants [7]. A study of the construction industry [35] highlights that several nZEB research and analysis tools have been introduced over the past few years, but very few have been actually practiced in the industry identifying a huge gap in implementation and achieving high performance buildings. Deep retrofit programs are underway to achieve low energy buildings with different optimisation goals such as EBC Annex 61 [36] and ECBCS Annex 52 [37].

1.6.2 National definitions

Article 9 of the Energy Performance of Buildings Directive (EPBD) directs EU member states to develop nZEB definitions for existing buildings [38]. While 13 jurisdictions have so far
identified criteria for existing residential buildings, only 11 countries (Austria, Brussels Capital Region, Bulgaria, Cyprus, Czech Republic, Denmark, France, Italy, Latvia, Lithuania, and Slovenia) have established definitions for existing non-residential buildings.

Table 1.2 nZEB energy levels defined by EU member states for new and existing buildings [39]

<table>
<thead>
<tr>
<th>Country</th>
<th>Residential Buildings (kWh/m²/yr) or Energy Class</th>
<th>Non-Residential Buildings (kWh/m²/yr) or Energy Class</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>New</td>
<td>Existing</td>
</tr>
<tr>
<td>Austria</td>
<td>160</td>
<td>200</td>
</tr>
<tr>
<td>Belgium</td>
<td>45 (Brussels region)</td>
<td>~54</td>
</tr>
<tr>
<td></td>
<td>30 (Flemish region)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>60 (Walloon region)</td>
<td></td>
</tr>
<tr>
<td>Bulgaria</td>
<td>~30-50</td>
<td>~40-60</td>
</tr>
<tr>
<td>Cyprus</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Czech Republic</td>
<td>75%-80% PE</td>
<td>75%-80% PE</td>
</tr>
<tr>
<td>Germany</td>
<td>40% PE</td>
<td>55% PE</td>
</tr>
<tr>
<td>Denmark</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Estonia</td>
<td>50 (detached house)</td>
<td>n/a</td>
</tr>
<tr>
<td></td>
<td>n/a</td>
<td>100 (office buildings)</td>
</tr>
<tr>
<td></td>
<td>n/a</td>
<td>130 (hotels, restaurants)</td>
</tr>
<tr>
<td></td>
<td>n/a</td>
<td>120 (public buildings)</td>
</tr>
<tr>
<td></td>
<td>n/a</td>
<td>130 (shopping malls)</td>
</tr>
<tr>
<td></td>
<td>100 (apartment blocks)</td>
<td>n/a</td>
</tr>
<tr>
<td></td>
<td>n/a</td>
<td>100 (day care centres)</td>
</tr>
<tr>
<td></td>
<td>n/a</td>
<td>270 (hospitals)</td>
</tr>
<tr>
<td>France</td>
<td>40-65</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>n/a</td>
<td>110 (offices with AC)</td>
</tr>
<tr>
<td>Croatia</td>
<td>33-41</td>
<td>n/a</td>
</tr>
<tr>
<td>Hungary</td>
<td>50-72</td>
<td>n/a</td>
</tr>
<tr>
<td>Ireland</td>
<td>45 (Energy load)</td>
<td>75-150</td>
</tr>
<tr>
<td>Italy</td>
<td>Class A1</td>
<td>Class A1</td>
</tr>
<tr>
<td>Latvia</td>
<td>95</td>
<td>95</td>
</tr>
<tr>
<td>Lithuania</td>
<td>Class A++</td>
<td>Class A++</td>
</tr>
<tr>
<td>Luxembourg</td>
<td>Class AAA</td>
<td>n/a</td>
</tr>
<tr>
<td>Malta</td>
<td>40</td>
<td>n/a</td>
</tr>
<tr>
<td>Netherlands</td>
<td>0</td>
<td>n/a</td>
</tr>
<tr>
<td>Poland</td>
<td>60-75</td>
<td>n/a</td>
</tr>
<tr>
<td>Romania</td>
<td>93-217</td>
<td>n/a</td>
</tr>
<tr>
<td>Spain</td>
<td>Class A</td>
<td>n/a</td>
</tr>
<tr>
<td>Sweden</td>
<td>30-75</td>
<td>n/a</td>
</tr>
<tr>
<td>Slovenia</td>
<td>45-50</td>
<td>79-90</td>
</tr>
<tr>
<td>Slovakia</td>
<td>32 (apartment buildings)</td>
<td>n/a</td>
</tr>
<tr>
<td></td>
<td>n/a</td>
<td>34 (schools)</td>
</tr>
<tr>
<td></td>
<td>54 (family houses)</td>
<td>n/a</td>
</tr>
</tbody>
</table>

Notes: PE - Primary energy; n/a - not available
Ireland has followed these countries by setting up primary energy use requirements for existing buildings in the draft definition of the national nZEB plan [28]. A brief summary of nZEB energy levels specified by EU member states for residential and non-residential buildings is given in Table 1.2. The definitions provided by the member states are either a numerical range, a percentage of primary energy consumption, or refer to an energy class. A few countries have identified the definitions for specific typology of building (school, offices, hotels etc.) such as Slovakia, Estonia and France.

1.6.3 nZEBs in Ireland

The Irish government introduced prescriptive energy efficiency requirements for buildings in 1991. The first performance-based code was introduced following the release of the EPBD in 2002 [40], with the latest code being further strengthened to reflect the requirements of the 2010 EPBD recast [3]. Part L (updated in 2017) of Building Regulations [41] and the surrounding national policies introduce methods, tools and requirements to ensure better energy performance of buildings. These methods and requirements include mandatory computer modelling for new buildings, low U-value requirements, air-tightness testing requirements for all new dwellings, bioclimatic design considerations, mandatory renewable energy requirements, robust pre-occupancy commissioning and a national target to build nZEB by 2020. Ireland’s Part-L of Building Regulations is a performance-based code that requires a mandatory energy performance calculation to establish the Energy Performance Coefficient (EPC) and Carbon Performance Coefficient (CPC) to be compared with a relevant reference building [41],[42]. The Building Regulations are divided in two sections, ‘dwellings’ (2017) and ‘buildings other than dwellings’ (2017) with specific requirements outlined for each type of building. The regulations address most thermal envelope requirements and energy-using systems in the calculation, including heating, ventilation and air conditioning (HVAC), hot water and lighting. These regulations have been updated with the focus on achieving nZEB and direct its users to achieve them by addressing the regulations in new and existing buildings.

The nZEB definition of newly-built dwelling by the Department of the Environment, Community and Local Government (DECLG) in Ireland demands an Energy Performance Coefficient (EPC) of 0.302 and Carbon Performance Coefficient (CPC) of 0.305 with primary energy consumption of 45kWh/m²/yr. However, the target for existing dwellings that will receive significant renovation after 2020 is 75-150 kWh/m²/yr. (including space and water
heating, lighting and ventilation) [43]. For non-residential buildings, an improvement of 50-60% in the energy and carbon performance is proposed.

The fourth National Energy Efficiency Action Plan (NEEAP IV) was released recently to reinforce the national targets of reducing primary energy consumption across all sectors focusing on nZEBs [44]. The Standard Recommendation S.R.54:2014 has been developed to provide guidance on the energy efficient retrofits of dwellings [45]. Through this Recommendation, technical guidance is provided on the energy efficient retrofits of dwellings having particular regard to fabric and building services, the application of retrofit measures on a whole dwelling basis, general building science, and the management of retrofit projects in respect of dwellings. The intended audience for this Standard Recommendation are property managers, designers, specifiers and installers working on energy efficient retrofit projects for dwellings [45]. However, a lack of rigorous measures for existing non-domestic buildings to achieve nZEBs can be noticed in the current regulations.

1.6.3.1 nZEB Market conditions
Ireland’s residential housing stock was identified as being amongst the least energy efficient in Northern Europe, but recent studies [46] show a strong reduction in household energy consumption in Ireland by 4%/year since 2008. It corresponds to the energy efficiency improvements driven by various types of policy measures and higher energy prices since 2004. Large energy efficiency improvements in Ireland of approx. 5%/yr can be seen between 2008 – 2012 (Figure 1.6, the blue line indicates the average rate of efficiency of around 1.5%/year according to the Article 7 of Energy Efficiency Directive [46]).

Figure 1.6 Energy efficiency improvement by country [46]
The Irish government have implemented a large number of renovation and retrofit programs since the introduction of EPBD in 2002 [47]. The programmes are listed in Table 1.3 with their time of induction and purpose. Sustainable Energy Authority of Ireland (SEAI) have administered most of the programs/measures since 2008.

**Table 1.3 Measures on energy efficiency and renewable energy in Ireland [47]**

<table>
<thead>
<tr>
<th>Sector</th>
<th>Title</th>
<th>Status</th>
<th>Type</th>
<th>Starting Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Household</td>
<td>Building Regulations 1991</td>
<td>Completed</td>
<td>Legislative/Normative</td>
<td>1992</td>
</tr>
<tr>
<td>Household</td>
<td>Building Regulations 1997</td>
<td>Completed</td>
<td>Legislative/Normative</td>
<td>1998</td>
</tr>
<tr>
<td>Household</td>
<td>House of Tomorrow</td>
<td>Completed</td>
<td>Financial</td>
<td>2001</td>
</tr>
<tr>
<td>Household</td>
<td>Warmer Home Scheme (Low Income Housing Strategy)</td>
<td>Ongoing</td>
<td>Financial</td>
<td>2002</td>
</tr>
<tr>
<td>Household</td>
<td>Energy Conservation Standards for New Dwellings (Revised Building Regulations) 2002</td>
<td>Completed</td>
<td>Legislative/Normative</td>
<td>2003</td>
</tr>
<tr>
<td>Household</td>
<td>The Greener Homes Scheme</td>
<td>Completed</td>
<td>Financial</td>
<td>2006</td>
</tr>
<tr>
<td>Household</td>
<td>Low Carbon Homes Scheme</td>
<td>Completed</td>
<td>Financial</td>
<td>2006</td>
</tr>
<tr>
<td>Household</td>
<td>Building Regulations 2008</td>
<td>Ongoing</td>
<td>Legislative/Normative</td>
<td>2008</td>
</tr>
<tr>
<td>Household</td>
<td>Upgrade of Older Housing Stock - Home Energy Savings Scheme &amp; Housing Aid for Older People Scheme</td>
<td>Completed</td>
<td>Financial</td>
<td>2009</td>
</tr>
<tr>
<td>Household</td>
<td>Building regulations 2011</td>
<td>Ongoing</td>
<td>Legislative/Normative</td>
<td>2011</td>
</tr>
<tr>
<td>Household</td>
<td>Better Energy Homes (Residential Retrofit)</td>
<td>Ongoing</td>
<td>Legislative/Normative</td>
<td>2011</td>
</tr>
<tr>
<td>Household</td>
<td>Smart Metering</td>
<td>Ongoing</td>
<td>Information/Education/ Training</td>
<td>2016</td>
</tr>
<tr>
<td>Tertiary</td>
<td>Demand Side Management Measures</td>
<td>Ongoing</td>
<td>Information/Education/ Training</td>
<td>1991</td>
</tr>
<tr>
<td>Tertiary</td>
<td>Building Regulations 1991</td>
<td>Completed</td>
<td>Legislative/Normative</td>
<td>1992</td>
</tr>
<tr>
<td>Tertiary</td>
<td>Building Regulations 1997</td>
<td>Ongoing</td>
<td>Legislative/Normative</td>
<td>1998</td>
</tr>
<tr>
<td>Tertiary</td>
<td>Building Regulations 2005</td>
<td>Completed</td>
<td>Legislative/Normative</td>
<td>2005</td>
</tr>
</tbody>
</table>
A number of programs have been undertaken for the household and tertiary sector for improvement of energy efficiency since the 1990s. The distribution of the programs was based on financial, legislative, normative, co-operative, education and information types (Figure 1.7). A rise in the number of legislative/normative and financial programs in the household sector was observed between 2008-2013. However, for the tertiary sector a bulk of informative, financial and legislative/normative programs were introduced in Ireland to support the uptake of energy efficiency improvements during 2008-2013.

<table>
<thead>
<tr>
<th>Tertiary</th>
<th>Programme</th>
<th>Status</th>
<th>Type</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tertiary</td>
<td>Bioheat Boiler Deployment Programme</td>
<td>Ongoing</td>
<td>Financial</td>
<td>2006</td>
</tr>
<tr>
<td>Tertiary</td>
<td>Assessment of Renewable Energy Alternatives at Design Stage</td>
<td>Ongoing</td>
<td>Legislative/Normative</td>
<td>2008</td>
</tr>
<tr>
<td>Tertiary</td>
<td>Air Conditioning</td>
<td>Ongoing</td>
<td>Legislative/Informative</td>
<td>2008</td>
</tr>
<tr>
<td>Tertiary</td>
<td>Better Energy Workplaces</td>
<td>Completed</td>
<td>Financial</td>
<td>2011</td>
</tr>
<tr>
<td>Tertiary</td>
<td>Public Sector Retrofit (Including SEAI Public Sector Programme)</td>
<td>Ongoing</td>
<td>Information/Education/Training</td>
<td>2011</td>
</tr>
<tr>
<td>Tertiary</td>
<td>Commercial/Industry Sector Retrofit</td>
<td>Ongoing</td>
<td>Financial</td>
<td>2014</td>
</tr>
</tbody>
</table>
The provision of the incentives supports the market penetration of nZEBs, but to what extent these are distributed among the participants of the retrofit industry poses a big question. The adoption of innovative retrofit products indicates maturity levels of the market towards nZEBs. The development of market for the nZEB is miss-managed in terms of intensity and training activities, management support to new products, inspection and quality control, and interaction among different functional departments of the construction sector, such as planning and policy units. The launch of nZEBs was initiated by a program known as the nZEB 2021 ‘Open Doors Days’ campaign [48], an Intelligent Energy Europe programme aiming to give hands-on experiences of building and living in nearly zero-energy buildings to visitors during the Open Doors Days events. Energy Action is coordinating the Irish nZEB Open Doors campaign [49]. The ongoing ‘Power of One’ campaign [50] has brought the message of the importance of energy efficiency to all consumers and has provided practical steps to help the public improve their own personal energy efficiency through small changes in behaviour and choices. As per the Central Statistics Office data, dwellings built during 2015-18 were more-energy efficient (96% of newly built dwellings were BER A rated) than previously built dwellings in 2010-2014 (36% of newly built dwellings were BER A rated) [51]. Approximately 27% of the non-domestic construction has been awarded a BER of A between 2015-17 (based on the audit conducted on 758 constructed buildings during this period), compared to 8% during 2010-14 [52]. However, none of the buildings built prior to 2005 were reported to have a BER of A. This highlights the opportunity to upgrade the non-domestic sector and develop appropriate strategies for achieving nZEB.

Figure 1.7 Energy efficiency measure patterns for household and tertiary sector over time [47]
Chapter 1. Introduction

There are several barriers to and reasons for the Irish retrofit market failure, as mentioned in a report by Joseph Curtin in 2008 [53]:

- High upfront costs and discount rates
- Split incentives between tenants and owners
- Lack of reliable information
- Uncertainty in the mind of customers
- Availability and reliability of energy service providers/contractors
- Inconvenience during retrofits
- Collective action from homeowners

Even though these barriers and reasons were identified 10 years ago, they are still applicable today, albeit reduced somewhat since 2009 but with still some way to go [54]. Many of these are also applicable to other EU member states.

1.7 Research framework

In this section, the outline of the research framework is presented elaborating on the preliminary inquiry conducted before the main research. The research aim and objectives were developed post this inquiry and the methodology was formulated using combined research methods.

1.7.1 Scoping study: Identification of gaps

An initial scoping study was conducted on the topic of achieving nearly zero-energy buildings (nZEBs) through retrofitting of existing buildings focusing on the health and well-being of occupants. The intent of the scoping study was to explore a broad research topic that has not been reviewed comprehensively before. A preliminary literature review was first conducted to understand and examine the extent, range, and nature of research activity in the domain of stakeholder analysis, Indoor Environmental Quality (IEQ) and its impact on occupants, building energy modelling, optimisation and deep-retrofitting strategies. The review enabled the identification of gaps in theory. Following this, a stakeholder investigation was conducted to understand the gaps in industry practices, state-of-the-art and readiness of the Irish retrofit industry sector compared to the overall European context. The main objective of the assessment was to deepen the understanding of the retrofit scenario in Ireland from the perspective of the stakeholders within the construction industry and identify the opportunities for further work and direction within the scope of this thesis.
Chapter 1. Introduction

Hence, the broad research questions investigated through the scoping study were:

- What is the relationship and impact of retrofits on IEQ and energy performance?
- What are the barriers, gaps and challenges in the Irish retrofit industry to reach the nZEB goals?

The scoping study was designed using combined research techniques of literature review, surveys, workshop and interviews and these are presented in detail in Chapter 2 and Chapter 3. The findings from the scoping study provided a greater understanding of the existing gaps and provided opportunities for some of them to be considered in this research and these included:

- Absence of field-studies and monitoring data in temperate-oceanic climate on IEQ for post-war non-domestic buildings (>35 yrs. old).
- Low-quality auditing practices and use of standards for diagnosis of problems in the existing buildings.
- Quantification of the impact of retrofit on IEQ (thermal, visual and acoustic comfort and indoor air quality) and energy performance.
- Lack of expertise and decision-making on non-domestic deep-retrofits and its cost-effectiveness.
- Role of building energy models in deep-retrofits and the impact of uncertainty in inputs on its predictions.
- Development of building energy models for the application and use in IEQ studies.
- Importance of integrated deep-retrofit strategies for single and staged retrofit approaches and its application on non-domestic buildings.
- Application of multi-objective optimisation for the identification of trade-offs for deep-retrofit of existing buildings.
- Absence of guidance for conducting deep-retrofits and its benefits in terms of comfort and energy performance.
- Feasibility of long-term renovation strategies for non-domestic buildings.
1.7.2 Aim and objectives
Following the scoping study, the main aim of this research was the development of decision-making support for deep-retrofit of non-domestic buildings (>35 yrs. old) to improve energy performance and Indoor Environmental Quality (IEQ). Therefore, to achieve this aim the following objectives were formulated:

- Identifying and conducting a field study (non-domestic building) to evaluate the influence of retrofit on occupant comfort, environmental conditions and energy performance.
- Systematic development of a whole building energy simulation model using the field study and audit data in different resolutions for retrofit analyses.
- Evaluating the role of uncertainty analysis prior to calibrating the model of existing buildings and its impact on outputs.
- Calibrating the developed model against the energy and environmental reference data for accurate assessment of the existing and future performance of the field study building including IEQ.
- Identification of retrofit measures for the field-study building based on detailed audits and field measurements and evaluating them using the calibrated model.
- Developing decision-making support using the calibrated model and identifying appropriate retrofitting strategies in single or multiple stages to achieve nZEB performance, cost-optimality and improved Indoor Environmental Quality (IEQ).

1.7.3 Methodology
To fulfil the above objectives, the research methodology was designed in three main stages as presented in Table 1.4. In the first-stage, synthesis from the scoping study guided a detailed systematic field-study of a non-domestic building that was partially retrofitted using various research techniques and tools for evaluation of IEQ, energy efficiency and its inter-relationships. Short-term and long-term analyses was conducted to evaluate the influence of retrofit on occupant comfort. During the second-stage, a calibrated building energy model was developed after intense sensitivity analysis of the simulation inputs using the data collected during the first-stage. Further, in the third-stage, the calibrated building energy model was utilised to evaluate different deep-retrofit solution packages using multi-objective optimisation.
for the field study building and evaluate single and staged approaches to assist in decision-making for retrofits involving objectives of cost, energy and comfort.

Table 1.4 Description of methodology

<table>
<thead>
<tr>
<th>I</th>
<th>Field study</th>
<th>• Field study (surveys, audits, measurements) of a partially-retrofitted university building&lt;br&gt;• Standard’s based Indoor Environment Quality (IEQ) assessment&lt;br&gt;• Short-term and long-term analyses</th>
</tr>
</thead>
<tbody>
<tr>
<td>II</td>
<td>Building energy simulation model development and calibration</td>
<td>• Building energy simulation modelling&lt;br&gt;• Sensitivity analysis of simulation input parameters&lt;br&gt;• Automated calibration of the model using genetic algorithm</td>
</tr>
<tr>
<td>III</td>
<td>Decision-making using multi-objective optimisation</td>
<td>• Evaluation of different deep-retrofit measures using multi-objective optimisation for single-step and staged retrofits&lt;br&gt;• Outlining impact of deep-retrofit on energy consumption, indoor environmental quality (discomfort hours, IAQ) and life cycle- costs (LCC)&lt;br&gt;• Deep-retrofit solution packages for achieving nZEB performance</td>
</tr>
</tbody>
</table>

1.7.4 Scope of the research

The research presented in the thesis deals with the deep-retrofit of existing buildings to achieve nZEB performance and support decision-making. Since the research domain is very broad, therefore, certain boundaries and limitations were set. The research presented is focused on investigating deep-retrofit at EU level as the existing building stock share certain similarities. Due to limited outreach in the European retrofit market, the stakeholder investigation was limited to the Irish context where survey, workshop and interviews were conducted. Although there is a difference in the climatic conditions of member states, the proposed methodology considers the application of techniques and methods into other geographical areas. Since the EU building stock is varied and diverse, the scope of the research methodology was limited to investigating a university building (non-domestic) as there is a large portion of exiting stock from this category aged between 30-50 years in the EU. With the intention to address similar building typologies in the EU member states and scale its impact the field study building was selected in this research. The application of the research work can also be extended to other non-domestic building typologies.
1.8 Thesis outline

The thesis structure comprises of seven chapters and associated appendices, as outlined in Figure 1.8. The first chapter introduces the subject, motivation and research framework. The second chapter elaborates on the theoretical background via a literature review. From Chapter 3 to Chapter 6, the published/submitted articles are presented with an article overview. Finally, Chapter 7 collates the overall research findings and concludes the research with future work and practical implications of this work.

Chapter 1 of this thesis presents the introduction to the research topic, motivation and its relevance in the current scenario within the European Union. This chapter discusses the energy consumption and renovation trends, along with the status of nearly zero-energy buildings in the context of retrofits. The aim and objectives of this research are presented outlining the essential areas required to be studied and investigated to develop the decision-making support. Further, the description of the methodology is presented encompassing all the objectives.

Chapter 2 highlights the current literature and state of the art on several aspects such as stakeholder investigation, performance evaluation of buildings and their analyses. The main principles of Indoor Environmental Quality (IEQ) in the built-environment and its impact on occupants are presented. Also, the significance of integrated strategies for retrofits, whole building energy modelling, uncertainty analysis and calibration are discussed, along with Life-Cycle Cost (LCC) analysis. This chapter presents the gaps identified in theory.

Chapter 3 introduces the scoping study carried out through a stakeholder investigation. The main objective of this study was to assess the attitudes and approaches of Irish retrofit industry professionals towards achieving nZEBs. A comprehensive three-tier methodology was used in the investigation that involved the use of surveys, workshop and interviews with the participants from Ireland. The main barriers, gaps and challenges were identified through this study in the industry practices which further guided the course of this research.

Chapter 4 presents a field study that was conducted on a partially-retrofitted university building to assess the interactions of several building performance parameters through detailed audit, surveys and measurements. The main aim of this study was to follow a standardised approach (based on ASHRAE 55 [60], EN15251 [61] and ISO 7730 [62]) on conducting
assessments on existing buildings that could guide in identifying the issues of IEQ (thermal comfort, visual comfort, acoustic comfort and Indoor Air Quality) and building energy performance. These assessments provided an approach and prescriptive path to recognise the retrofit measures that are discussed in the next chapters.

Chapter 5 outlines the development and analysis of a Building Energy Model (BEM) which is based on the field study presented in Chapter 4. In this chapter, an uncertainty analysis is conducted using the Morris method [63] to determine the sensitive parameters for calibration. The BEM of the existing field study building is calibrated through a novel robust multi-stage calibration methodology using an automated approach (NSGA-II) and considering the performance parameters. The measured energy consumption and indoor air temperature were used for the calibration. The calibrated model is further validated using additional datasets.

Chapter 6 advances the main methodology to analyse several retrofit measures for the field study building. A multi-objective optimisation was conducted on assessing the appropriate deep-retrofit solution packages. Further, a cost-optimal analysis was conducted to evaluate the best solutions for the retrofitting of the building to achieve nZEB performance. The results are presented for the three objectives of cost, comfort and energy consumption.

Chapter 7 discusses the main results of the research and overall conclusions based on the findings from Chapter 2, 3, 4, 5 and 6. The appendices present further details of different aspects used within this research. Some of these include (i) surveys and interview questionnaires for stakeholder investigation, (ii) point in time surveys for IEQ assessment and data collection strategy, (iii) building energy model inputs (iv) calibration scripts and jEPlus (results extraction code), and (v) a shortened version of EnergyPlus file (text file)
Figure 1.8 Research outline scheme
1.9 References


[29] BPIE, Europe’s buildings under the microscope. Belgium, Brussels: Buildings


Chapter 1. Introduction


Chapter 2 : Literature review
2.1 Chapter overview

Retrofitting of existing buildings to make them more energy efficient and improve their indoor environmental quality (IEQ) to benefit occupants’ health and wellbeing requires understanding of the requirements of key stakeholders, diverse knowledge on the subjects of IEQ (thermal, acoustic and visual comfort, Indoor Air Quality), whole building energy modelling, life-cycle cost analysis, and optimisation algorithms and methods. An understanding of the international standards for evaluation of building IEQ, energy consumption analysis, and retrofit strategies is essential to develop research inquiries. This chapter, therefore, presents Section 2.2 focusing on the method and relevance of the stakeholder analysis. Section 2.3 elaborates on the core principles and assessment of IEQ and Section 2.4 outlines the impact of IEQ on occupant performance and its significance. Further, in Section 2.5, a discussion is presented on the whole building energy models, uncertainties and calibration. In Section 2.6, the perspective of integrated retrofits is presented focusing on improving the existing buildings using optimisation. Section 2.7 describes the basics of Life-Cycle Costs (LCC) and its role in retrofit decision making.

2.2 Stakeholder analysis

A stakeholder analysis is a systematic process to understand and analyse the qualitative information to determine the interest of involved stakeholders, their requirements, needs and issues in developing policies, programs, projects or other actions in any sector or industry [1]. Stakeholders are the actors, experts, individuals or groups involved/ having a stake in a particular interest, action or programme at any level such as global, national, regional, local or community [2], [3]. One of the main aims of stakeholder analysis is to engage and promote public participation. The role of stakeholders is crucial in identifying and establishing guidelines, as well as developing solutions and creating opportunities to tackle the issues regarding social, economic, environmental and technical aspects [4].

A few major steps are followed for a successful stakeholder analysis that can be tailored for the specific nature of investigation [1]. The first step is to identify the purpose of analysis and uses of the results, along with the plan and timeline required for investigation. In the second step of stakeholder analysis, key stakeholders are identified based on different methods such as their types, roles and interests that are directly or indirectly related to the area of investigation [5]. In the third step, it is important to identify the tools to be used and adapt them for gathering the
data and its analysis. Tools such as stakeholder mapping, power interest matrix, and cross-charts are adapted for analysing the data collected via popular data collection methods such as online surveys, interview questionnaire and group discussions/ workshops [6], [7]. The last step is to group and accurately generalize the findings using methods of thematic analysis or matrices for large qualitative datasets [8].

The scoping study phase of this research focuses on Irish construction industry stakeholders involved in the energy and building sector, specifically associated with retrofitting. Therefore, different roles and types of stakeholders can initially be identified based on work done to co-create the national renovation strategy for Ireland [9]. A study in Spain identified cost-effective opportunities for improving the energy performance of buildings through a stakeholder analysis, where different stakeholders were identified such as owners, clients, financial, energy retrofit providers among others [10]. In a working paper of a study conducted in the UK, the barriers and triggers were studied in retrofitting private and commercial properties through a stakeholder analysis where participants were from the private sector, local government, non-government organisations (NGOs) and academics [11]. Another report from the World Business Council for Sustainable Development (WBCSD) [12] on the energy efficiency of buildings outlined the different stakeholders involved in the supply chain of building construction and these included the architects, engineers, real-estate companies, owners, local authorities, developers and financiers.

Stakeholders are generally analysed for their importance, their role and impact that must be assessed based on the subject under consideration [5]. The exercise for the identification of main stakeholders can also be done through brainstorming sessions [2]. Another important aspect that can be studied in stakeholder analysis is the relationship and cooperation between different stakeholders for understanding disagreement levels. The relationships among different stakeholders of the value chain in the energy efficiency industry as identified by the WBCSD is given in Figure 2.1.
There are several actors and experts involved in the Irish retrofit construction industry. Recently, the growth of the retrofit industry in Ireland has caused conflicting requirements and widespread uncertainties regarding the involvement of individual professionals, organisations and authorities in public and private sector, small and medium enterprises, owners and various other businesses. The barriers exist in taking collective decisions and following a prescriptive path outlined by the EU to achieve energy efficiency, especially nZEB levels, through renovation. There is a greater demand for higher skills and expertise in the supply value chain for energy efficient retrofitting of the existing building stock in Ireland [13]. To understand the existing issues of the retrofit industry, in this research a detailed stakeholder investigation was conducted using the state of art and is presented in Chapter 3.

Further literature presented in this chapter focuses on the physical, technical and performance evaluation aspects of this research.

2.3 Indoor Environmental Quality (IEQ)

In today’s modern society, people spend approximately 90% of their time living and working in buildings; therefore, IEQ in buildings has become an issue of increasing concern [14]. In this regard, a large body of social science and environment-behaviour research has indicated that the improvement of IEQ has health benefits to the occupants [15]–[17]. The US Department of Energy established an International Performance Measurement and Verification Protocol (IMPVP) in 1996 for concepts and practices for improved IEQ, which can be associated with energy conservation measures (ECMs) [18]. There are many envelope-related
improvements that have been noted to improve IEQ, especially with respect to thermal comfort, ventilation, lighting and acoustics. Current legislation of EPBD [19] and EED [20] have pushed member states in Europe to address the existing building stock of Europe through energy efficient retrofits and achieve near zero-energy building performance. It has also presented an opportunity to investigate the feasibility of improving both IEQ and energy efficiency in existing building stock with well-designed retrofit measures.

Different retrofit measures under shallow, medium or deep-retrofits hold great promise for improving the energy efficiency of buildings. In conjunction with a raised awareness of energy efficiency, IEQ is taking central attention as mentioned in the multi-annual roadmap of 2020 [21]. However, the impacts of retrofits are not completely addressed with respect to IEQ in a cost-effective manner [22]. Deep retrofits (saving over 60% energy) can bring intangible benefits of enhanced work performance and improved productivity in indoor environments such as offices, schools, colleges and commercial establishments. Productivity can be defined as the ratio of outputs (e.g. products, services and activities) to the inputs (e.g. material, capital, energy, labour) implemented to produce the outputs [16]. In this section, a comprehensive literature review is presented from the existing research and is analysed with respect to their potential applicability in assessing and improving IEQ through retrofits and how they can be used to bring benefits. The environmental factors of thermal comfort, visual comfort, acoustic and indoor air quality (IAQ) define IEQ [23]. Each of these are discussed in the following subsections with respect to the latest standards and research.

2.3.1 Thermal comfort

According to ASHRAE 55 [24] and ISO 7730 [25] *‘thermal comfort is that condition of mind which expresses satisfaction with the thermal environment’*. ASHRAE 55 and ISO 7730 specify the combination of indoor thermal environmental parameters (temperature, radiant temperature, humidity and air velocity) and personal parameters (metabolic rate and clothing insulation) for acceptable comfort conditions to occupants. There are two models to identify the thermal sensation in a space; namely, the rational model (heat balance) and adaptive comfort model in both the standards [24], [25].
2.3.1.1 Overview of thermal comfort standards

The introduction of thermal comfort assessments for improving indoor environmental conditions for human occupancy has been studied and researched extensively by Fanger [27], Bedford [28] and Givoni [29]. There is a strong correlation between energy consumption and international thermal comfort standards set for buildings [30]. These standards have been included in current and widely acceptable international standards such as ISO-7730 [25], ASHRAE-55 [24], and EN 15251 [26]. The application of these standards is defined to determine comfort conditions for new and relatively new existing buildings. They are not only confined for the evaluation of office environments but can also be used for other types of work environments such as classrooms and laboratories. However, there are no clear indications of how to apply these standards to non-domestic existing buildings [31]. The scope of these standards also excludes the guidance for the design of thermal envelopes and other buildings systems leaving room to investigate the co-relations that exist with thermal comfort criteria. There are no standard methods which can be used by designers for the retrofitting of envelopes and systems in order to achieve the space conditions as described in standards under different categories [24]. This situation deepens with the ageing of existing non-domestic buildings stock, where deep retrofits are required to achieve a greater degree of thermal comfort in an energy efficient and cost-effective manner in tandem with other building systems. Thermal discomfort leads to lower productivity levels in the workplaces and is an important driver for the renovation of non-domestic buildings [32]. The introduction of the EPBD (Energy Performance Building Directive) and its recast demands adaptation of current building standards when renovation or retrofitting of existing buildings [19], [33].

A literature study affirmed that among indoor environmental conditions, thermal comfort had been ranked higher or given primary importance than visual, acoustic comfort and indoor air quality [34]. For assessment of indoor thermal comfort conditions, a range of thermal comfort criteria are described in the standards and are widely acceptable by researchers across the world. These criteria are discussed below in detail.

2.3.1.2 Thermal comfort models

Over the past 100 years, many research efforts have been devoted to developing indices and models predicting the thermal sensation of people. Thermal comfort prediction models generally are mathematical models of the relationship between one or more environmental factors and certain occupant factors. The main aim of comfort models is to provide a single
index that encompasses all relevant parameters. A chronological review of current knowledge on thermal comfort shows two different approaches: heat balance approaches/climate chamber tests and adaptive approaches/field studies. The former, which is based on heat exchange processes of the body, has led to steady-state laboratory thermo-physiological models and standards (ASHRAE 55 [24], ISO 7730 [25]). The latter has led to adaptive thermal comfort models and standards: The American ASHRAE 55 and European EN15251 standards. Also, EN 15251 [26] specifies how to establish environmental input parameters for non-industrial buildings (single family houses, apartments, offices, educational buildings etc.) for thermal and energy performance calculations.

*Heat balance model (PMV/PPD)*

The heat balance model works in steady state conditions and assumes that the human body’s thermoregulatory system essentially maintain constant internal body temperature as depicted in Figure 2.2. It assumes that the thermal balance of the body is influenced by physical human activity (metabolic rate) and clothing preferences (clothing insulation). It also considers other environmental parameters: (i) air temperature, (ii) mean radiant temperature, (iii) air velocity and (iv) humidity.

The most notable models have been those developed by Fanger’s experiments in a controlled climate chamber on 1296 young Danish students, using a steady-state heat transfer model. In these experiments, subjects were dressed in standardised clothing and completed standardised activities. They were asked to vote on their thermal sensation with respect to how hot or cold they felt, using the seven-point ASHRAE thermal sensation numerical scale. This scale has the following range: +3 (hot), +2 (warm), +1 (slightly warm), 0 (neutral), -1 (slightly neutral), -2 (cool) and -3 (cold).
Fanger’s model is a combination of theories of heat balance and physiology of thermoregulation, which determines the ranges of comfortable temperatures for the occupants of the building. According to these theories, the human body employs physiological processes (e.g. sweating, shivering, regulating blood flow to the skin) in order to maintain a balance between the heat produced by metabolism and the heat lost from the body.

Thus, Fanger proposed the following formula:

\[ S = M \pm W \pm R \pm C \pm K - E - RES \]  \hspace{1cm} (2.1)

where \((S)\) heat storage, \((M)\) metabolism, \((W)\) external work, \((R)\) heat exchange by radiation, \((C)\) heat exchange by convection, \((K)\) heat exchange by conduction, \((E)\) heat loss by evaporation and \((RES)\) heat exchange by respiration (from latent heat and sensible heat). This equation related thermal conditions to the seven-point ASHRAE thermal sensation scale and became known as the “Predicted Mean Vote” (PMV) index. The PMV was then incorporated into the “Predicted Percentage of Dissatisfied” (PPD) index. The PMV and PPD generally
express thermal sensation as warm or cold for the whole body. However, a different criterion of local thermal discomfort can also be applied for design and dimensioning, which includes draught, vertical air temperature differences, floor temperature and radiant temperature asymmetry) as described in ISO 7730. This model is applied to people with light sedentary activity sensitive to local discomfort.

Fanger related PMV to the imbalance between the actual heat flow from a human body in a given environment and the heat flow required for optimum comfort at a specified activity by the following equation:

\[ PMV = f(t_a, t_{mrt}, v, p_a, M, I_{cl}) \]  

(2.2)

where \( t_a \) is air temperature [°C], \( t_{mrt} \) is mean radiant temperature [°C], \( v \) is relative air velocity [m/s], \( p_a \) is humidity (vapour pressure) [kPa], \( M \) is metabolic rate [W/m\(^2\)], and \( I_{cl} \) is clothing insulation [clo].

Further, based on the experimental studies on PMV, Fanger developed an empirical relationship of PMV with the ‘Predicted Percentage Dissatisfied’ (PPD) which predicts the percentage of people who feel more than slightly warm or cool [36]. The relationship between PMV and PPD is represented as:

\[ PPD = 100 - 95 \exp(-0.03353 \times PMV^4 - 0.219 \times PMV^2) \]  

(2.3)

This relationship indicates exact symmetry with respect to thermal neutrality i.e. (PMV=0). This means that if PMV=0, a minimum of 5% of dissatisfied people exists due to the difference in thermal comfort from person to person [30]. Figure 2.3 shows the relationship between PMV and PPD. The PMV/PPD model has been adopted by various standards e.g. ASHRAE Standard 55 and ISO 7730.
Depending on the ranges of PMV and PPD, four types of comfort ranges are defined in the new standard EN 15251 [26] based on the ASHRAE 55 and ISO 7730 standards. The comfort ranges forms one of the bases of the design and assessment of comfort and energy performance of new and existing buildings, as shown in Table 2.1. However, the application of recommended categories is not clearly defined for the old existing buildings.

Table 2.1 Recommended categories for design of mechanical heated and cooled buildings [26]

<table>
<thead>
<tr>
<th>Category</th>
<th>Explanation</th>
<th>PPD (%)</th>
<th>PMV</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>High level of expectation and is recommended for spaces occupied by very</td>
<td>&lt;6</td>
<td>-0.2 &lt; PMV &lt; +0.2</td>
</tr>
<tr>
<td></td>
<td>sensitive and fragile persons with special requirements like handicapped,</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>sick, very young children and elderly persons</td>
<td></td>
<td></td>
</tr>
<tr>
<td>II</td>
<td>Normal level of expectation and should be used for new buildings and</td>
<td>&lt;10</td>
<td>-0.5 &lt; PMV &lt; +0.5</td>
</tr>
<tr>
<td></td>
<td>renovations</td>
<td></td>
<td></td>
</tr>
<tr>
<td>III</td>
<td>An acceptable, moderate level of expectation and may be used for existing</td>
<td>&lt;15</td>
<td>-0.7 &lt; PMV &lt; +0.7</td>
</tr>
<tr>
<td></td>
<td>buildings</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IV</td>
<td>Values outside the criteria for the above categories. This category should</td>
<td>&gt;15</td>
<td>PMV &lt; -0.7; or</td>
</tr>
<tr>
<td></td>
<td>only be accepted for a limited part of the year</td>
<td></td>
<td>+0.7 &lt; PMV</td>
</tr>
</tbody>
</table>

2.3.1.3  **Adaptive comfort model**

The experiments to establish a relationship between PMV and PPD were carried out in climatic chambers. However, the adaptive approach investigates the dynamic relation between people
Chapter 2. Literature review

and their everyday environments, paying attention to the ‘adaptations’ people make to their clothing and to their thermal environment to secure comfort. The adaptive approach is derived from the field studies that determine the real conditions of the thermal environment. The heat balance model is generally applicable to the air conditioned spaces, but an adaptive model is applicable to the naturally conditioned spaces where the occupants adapt to the surrounding environment by three means: physiological (acclimatisation), behavioural (changing activity, clothing level, opening/closing windows) and psychological (cognitive, social and cultural variables) [37]. In real situations, people constantly interact with the immediate environment and adapt to it, making it comfortable for them. To apply this method in the field, the space must have operable windows with no mechanical cooling. There can be mechanical ventilation with unconditioned air. The space may have a heating system, but it must be inoperable while applying this method. One of the main inventions of the adaptive approach to thermal comfort is the expression of indoor comfort temperature as a function of outdoor temperature [38].

\[ T_{\text{com}} = A \times T_{\text{out}} + B \]  

(2.4)

where \( T_{\text{com}} \) = comfort temperature, \( T_{\text{out}} \) = mean outdoor temperature and \( A, B \) = constants.

A notable attempt to identify this expression was carried out by many prominent scholars; Nicol and Humphreys [39], [40] who worked on relationship of outdoor air temperature and indoor comfort, Auliciems [41] towards developing a psycho-physiological model, Nicol and Roaf [42] developed new indoor temperature standards, and Brager and de Dear [43] that studied the thermal adaptation in the built environment.

In naturally ventilated buildings, to calculate the adaptive comfort ranges during summer, the indoor air operative temperatures are predicted based on a function of the exponentially weighted running mean of the outdoor temperature when the heating system is not in operation [26]. The exponentially-weighted outside running mean temperature accounts for time-dependency over which the occupants adapt to their environment and it is calculated based on Equations (2.5) and (2.6).

\[ t_{\text{rm}} = (1 - \alpha)t_{\text{ed}-1} + \alpha t_{\text{rm}-1} \]  

(2.5)
where \( t_{rm} \) is the running mean indoor air operative temperature for today, \( t_{rm-1} \) is the running mean indoor air operative temperature for the previous day, \( t_{ed-1} \) is the daily mean external temperature for the previous day and \( t_{ed-2} \) is the daily mean external temperature for the day before and so on. Here, \( \alpha \) is a constant between 0 and 1, which is recommended as 0.8 for use if the running means are calculated weekly.

The indoor air operative temperature \((t_{rm})\) obtained for the rooms using the outdoor air temperature \((t_{ed})\) was used to determine the comfort ranges and cross evaluate them based on categories defined in EN 15251 [26] and are shown in Table 2.2.

<table>
<thead>
<tr>
<th>Category</th>
<th>Lower limits ( t_{i min} = 0.33t_{rm} + 18.8 )</th>
<th>Upper limits ( t_{i max} = 0.33t_{rm} + 18.8 + 2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>( t_{i min} = 0.33t_{rm} + 18.8 - 2 )</td>
<td>( t_{i max} = 0.33t_{rm} + 18.8 + 2 )</td>
</tr>
<tr>
<td>II</td>
<td>( t_{i min} = 0.33t_{rm} + 18.8 - 3 )</td>
<td>( t_{i max} = 0.33t_{rm} + 18.8 + 3 )</td>
</tr>
<tr>
<td>III</td>
<td>( t_{i min} = 0.33t_{rm} + 18.8 - 4 )</td>
<td>( t_{i max} = 0.33t_{rm} + 18.8 + 4 )</td>
</tr>
</tbody>
</table>

Note: These limits apply when \( 10 < t_{rm} < 30^\circ C \) for the upper limit and \( 15 < t_{rm} < 30^\circ C \) for the lower limit.

As per EN15251 [26], the adaptive comfort models are based on relationships between the outdoor and indoor temperatures; they already consider the occupants’ clothing and metabolic levels. The occupants can regulate the thermal conditions only by operating the windows and adjusting their clothing. As shown in Figure 2.4, the ranges of acceptability (operative temperatures) are plotted for the building against the prevailing mean outdoor air temperatures between 10-32.5 °C. The mean outdoor air temperature recorded in Summer was 16.0 °C. As shown in Figure 2.4, there are three bands for acceptability: (i) 60% acceptability (a wider band of acceptable operative temperatures) - Category III (ii) 80% acceptability (a narrow band of acceptable air temperatures) - Category II and (iii) 90% acceptability (a very narrow band of acceptable air temperatures for higher standard of thermal comfort) - Category I.
The adaptive approach to comfort have conditions compatible for low-carbon buildings [44].

Studies have shown that adaptive opportunities should be made an important part of future retrofit strategies for existing office buildings and adaptive comfort models predict the thermal sensation and thermal comfort better [45], [46].

Overall, as recommended in EN15251, the thermal comfort assessment should be done using models of PMV and PPD during the conditioned period and the adaptive comfort model during the natural ventilation period. Therefore, for standard based assessment these models were used in Chapter 4 of this research work.

### 2.3.2 Visual comfort

Visual comfort is defined in the European Standard EN12665 as “a subjective condition of visual well-being induced by the visual environment” [47]. Whilst visual discomfort can occur as a result of either too low or too high level of light. Visual comfort is a subjective measure dependent on certain factors such as illumination, luminance and brightness, luminous spectrum and risk of glare [47]. It has been reported that the presence of a good visual environment can add to the well-being and productivity of the occupants of a building [48]. There are minimum values of illuminance described in the standard EN 12464-1 [49] for work places in buildings that are required to be maintained to fulfil visual comfort and performance.
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needs [49]. A literature survey by Fabi et al. [50] regarded several psychological (attitudes), social (occupancy), physical (direct sunlight) and contextual (orientation) driving forces responsible for visual comfort in buildings. Occupants find it challenging to maintain good visual comfort as they have varied perception of glare and lighting levels at work places [51].

Some of the commonly used metrics for visual comfort are described below.

**Illuminance:** Illuminance at a surface $I_D$ is defined as a physical quantity measured in lux that is calculated as a ratio between the luminous flux falling on the surface with an area ($A_{ill}$).

$$I_D = \frac{d\phi}{dA_{ill}} \text{ [lux]}$$

(2.7)

where $I_D$ is illuminance [lux]; $\phi$ is luminous flux.

Therefore, illuminance is used as a single criterion to assess the availability of the amount of light falling at a single plane that is easy to measure using a lux meter. As per the standard EN-12464-1 [49], the minimum amount of illuminance required in a standard office work plane is 500 lux. This metric has certain limitations as; (i) it does not indicate any information about the quality of light, (ii) it does not refer to the type of light such as artificial or daylight, and (iii) it does not account for glare as it does not measure the observer’s perspectives.

**Daylight factor:** The daylight factor ($D_F$) is generally applicable under the Commission Internationale de l’Eclairage (CIE) overcast sky for access to daylight [52]. It is considered useful for the assessment of interior areas for daylight potential. Daylight factor does not consider the effects of direct sunlight exposure and is used for taking initial design decisions.

$$D_F = \frac{L_i}{L_o} \times 100\%$$

(2.8)

where $D_F$ is the daylight factor measured at a specific point [%]; $L_i$ is the available lux indoors at a specific point on a working plane [lux]; $L_o$ is the simultaneous available lux outdoors under a CIE overcast sky [lux].

As matter of fact, daylight which penetrates a room generally consists of three components:
(i) sky component, (ii) externally reflected component, and (iii) internally reflected component. The maximum daylight factor is near the windows which are due to the sky component. The average daylight factor can be used to assess the amount of daylight in early design stages.

\[
\text{Average } D_F = \frac{W}{A} \frac{T\theta}{(1-R^2)}
\]  \hspace{1cm} (2.9)

where \( W \) is the area of the windows [m\(^2\)]; \( A \) is total area of the internal surfaces [m\(^2\)]; \( T \) is the glass transmittance corrected for dirt; \( \theta \) is the visible sky angle in degrees from the centre of the window and \( R \) is the average reflectance of area \( A \).

**Spatial Daylight Autonomy:** Spatial Daylight Autonomy (sDA) is defined by the amount of daylight that a particular space receives during the standard operational hours (8:00 to 18:00) on an annual basis [53]. The hourly illuminance grids are used on the horizontal work plane to map the daylight received. sDA is calculated through computational simulation with parameters such as location and weather conditions throughout the year. The percentage of light that a specific point receives above a required threshold illumination within the annual daytime hours is termed as Spatial Daylight Autonomy (sDA) [53].

\[
sDA = \frac{\sum_i (w_f \cdot t_i)}{\sum t_i} \in [0, 1] \text{ with } w_f \begin{cases} 1 & \text{if } E_{\text{daylight}} \geq E_{\text{limit}} \\ 0 & \text{if } E_{\text{daylight}} < E_{\text{limit}} \end{cases}
\]  \hspace{1cm} (2.10)

where \( t_i \) is each occupied hour in a year; \( w_f \) is a weighting factor depending on values of \( E_{\text{daylight}} \) and \( E_{\text{limit}} \) that are the horizontal illuminance at a given point due to the sole daylight and the illuminance limit value, respectively.

sDA uses the geographic location and annual weather data containing the global, diffuse and direct irradiance measurements. Therefore, it is advantageous over the daylight factor, \( D_F \). Another benefit of this metric is the ability to calculate artificial light savings, which is possible by measuring the daylight received during each hour and providing sufficient artificial light if the total is below a minimum threshold.

**Daylight Glare Index:** The Daylight Glare Index (DGI) metric is used to consider the large glare sources such as windows and specifically diffuse sky visibility through the window. The
DGI metric was studied using human subjects in day lit interiors, where the sky brightness was measured, and it was given a position index and size [53]. This is not considered to be accurate when there is direct light or reflections present in the field of view. The relationship is defined as:

\[
DGI = 10 \log_{10} \left( \frac{0.478 \sum_{i=0}^{m} \left( \frac{L_{b}^{1.6} \omega_{i}^{0.8}}{L_{b}^{0.07} \alpha^{0.5} L_{win, i}^{1.6}} \right)}{L_{b}+0.07 \alpha^{0.5} L_{win, i}^{1.6}} \right) \tag{2.11}
\]

where \( L_{win} \) is luminance through the window [cd/m\(^2\)]; \( L_{b} \) is the background illuminance [cd/m\(^2\)]; \( P \) is the position index; \( \alpha \) is angular size of source in steradians as seen by the eye; \( \omega \) is the solid angle subtending by each source \((s)\) from the point of view of the observer, modified with respect to the field of view and Guth position index \((P)\) of each luminaire \(i\).

DGI is a correlation between the source of luminance, size and its position in the field of view having a background of sky luminance with a small percentage of the source luminance compensating for additional eye adjustment to the visible luminance. The value of DGI varies from 18 to 31, where 18 corresponds to barely perceptible glare and 31 or greater corresponds to intolerable glare.

A range of metrics are available to measure visual discomfort as discussed above. However, due to the ease in measurement and low-cost, the illuminance (lux) at the workplace is used as a common metric for the assessment of visual comfort (adequate lighting) in this research in Chapter 4. However, other illuminance-based metrics, such as Spatial Daylight Autonomy (sDA), correspond to measuring varying lighting conditions over the long-term [54]. Additionally, Daylight Glare Index (DGI) can also be used to measure the discomfort glare through large openings.

### 2.3.3 Acoustical comfort

Acoustic comfort is the presence of a comfortable acoustic environment without any uncomfortable noise [34]. Acoustic comfort is considered crucial for non-domestic buildings’ IEQ and is generally given high preference in offices and classrooms by occupants [55]–[57]. Occupants’ satisfaction in work-places can be achieved by speech privacy and comfortable sound levels, which is identified as the main problem regarding acoustic quality in office workstations [58]. Building elements play a significant role in offering external and internal
sound insulation [59]. There exists a number of methods to measure the sound levels in indoor spaces such as the loudness level (dB), equivalent sound pressure level (SPL), the noise rating (NR), the noise criterion curves (NC), balanced noise criterion, the preferred noise criterion (PR), and the room criterion (RC) [60].

Generally, the noise criteria of some indoor spaces and buildings are given in terms of A-weighted sound pressure levels (dB(A)) that is used with the instrument-measured sound levels for the relative loudness as perceived by the human ear in EN15251 [26]. These criteria apply to sources from both outside and inside the building, so that relative loudness is measured and used to limit the sound pressure levels inside the spaces. Noise levels can exceed these levels in case of occupants opening windows or the operation of HVAC units.

Retrofits can enable the reduction of indoor noise while addressing solutions for thermal comfort and energy efficiency [61]. Noise criteria do not directly relate to energy performance but depend on the opening of fenestrations. For example, to minimise outdoor noise occupants may close windows in summers and this would limit natural ventilation, consequently, cooling energy may be required to maintain indoor thermal comfort.

The metric of equivalent sound pressure levels was preferred and deemed suitable for Chapter 4 in this research due to its capability to consider indoor and outdoor noise effects on the human ear.

2.3.4 Indoor Air Quality (IAQ)

Poor Indoor Air Quality (IAQ) is known to have acute and chronic effects on the health of the occupants [62]. It is directly related to the ventilation rates and concentration of pollutants, which in turn are related to Sick Building Syndrome (SBS) which is used to describe situations where occupants have acute health and comfort effects [63]. In closed environments, IAQ is related to both chemical and physical causes, such as carbon oxides, CO and CO₂, environmental tobacco smoke, formaldehyde, volatile organic compounds (VOCs), ventilation rate, temperature, dampness, ionizing and non-ionising radiation [64]. Provision of outdoor air supply is known to provide acceptable perceived IAQ [65]. The World Health Organisation (WHO) has published indoor air quality guidelines for selected pollutants and their health effects with the target to ensure the provision of safer indoor environments [66]. A review of
studies on IAQ in schools by Daisey et al. [67] highlighted that many classrooms in the study were not adequately ventilated, causing health related symptoms due to the high concentration of CO$_2$, exposure to volatile organic compound (VOCs), moulds and microbial VOCs and allergens. Many studies investigated the influence of indoor carbon dioxide on occupants’ health and perceived air quality [68]–[70].

A study on the association of CO$_2$ with occupants’ health in commercial and institutional buildings of 30,000 occupants in about 400 buildings indicated the prevalence of SBS symptoms [71]. The CO$_2$ concentration is considered as an indicator of the rate of ventilation per occupant [71] and since there are no other low-cost methods available it is used as a reliable metric for measuring IAQ [72]. There is no common index for indoor air quality, therefore, it can also be expressed in terms of required ventilation or CO$_2$ concentrations [26]. A recent study among European countries showed that regulations for IAQ in domestic buildings were not comprehensive and need additional attention as they were recognised to be the most crucial aspect in building codes by the focus countries: Belgium (Brussels Region), Denmark, France, Germany, Italy, Poland, Sweden and the UK (England and Wales) [73]. Based on the findings from the literature, this research in Chapter 4 considered CO$_2$ as a proxy for measuring IAQ and also due to lower costs compared to other methods for measuring the concentration of indoor pollutants.

### 2.4 Impact of IEQ on performance and productivity

A direct relationship exists between the health and wellbeing of occupants and building energy efficiency upgrades and retrofits [74]. Improvement in indoor environment quality has tangible and intangible benefits to the occupants as outlined by studies on existing buildings [15]. Review of existing literature suggest that it is possible to quantify the productivity gains by improving the indoor environments [75]–[77], where productivity may be defined as the ratio of output (work performance) to input (investment and operational cost) incurred to any organisation as shown in equation 2.12 [78].

$$\text{Productivity} = \frac{\text{Work performance}}{\text{Investment (€ per occupant)} + \text{operational cost (including energy)}} \quad (2.12)$$

The average age of the existing non-domestic buildings in Europe is around 55 years and they comprise of commercial and public buildings, which are being used currently with
unsatisfactory IEQ. One of the main advantages of renovation is an improvement in productivity which in turn brings economic benefits [79]. Quantification of productivity can become a key driver for businesses to deep-retrofit their buildings and improve IEQ together with energy efficiency. Several scholars have explored links between several aspects of indoor environments and human performance such as thermal comfort, lighting and acoustics [78], [80]. Moreover, great attention is being payed to the relationship of indoor environments and energy performance and questions are being raised on how low, or nearly zero-energy, buildings [14] can also deliver optimal indoor environment quality, as described in EN15251 [81].

Productivity costs can be key in determining the overall cost strategy of deep-retrofits and how it impacts the work performance of the occupants inside work environments. However, the relationship between productivity and IEQ improvements are often not considered by building owners when deciding on whether to invest in upgrading their building to reduce energy consumption and improve comfort levels.

A model was proposed in ASHRAE transactions [82] for the estimation of the cost-effectiveness of improving office work through indoor environmental control. Figure 2.5 shows the conceptual model which illustrates the cost and benefit items integrated for consideration in building design changes, retrofits or operation. The model considers the annual investment costs, operation and maintenance costs and savings generated through the measures to improve IEQ. This model can be used in cost benefit analysis, but there is a requirement for empirical relationship equations between each of the boxes in Figure 2.5. The absence of such equations was determined as one of the major barriers to implementing this model to drive better indoor environments and it requires further research. However, the authors suggested that the linkages between the following are strong [82]:

i. High temperature to sick leave in winter.
ii. Low temperature to work performance.
iii. Building maintenance to complaints.
iv. Acoustic environment to task performance.
The scientific literature suggests that productivity can be measured in several ways, depending on the occupants and type of building. A study measured the effect of temperature on task speed and accuracy of the workers [83], whereas in another study it was measured by the number of calls made by the workers in a call centre [84]. The effects of sick building syndrome and absenteeism were also adopted as metrics to measure productivity [85]. The potential increase in productivity in the building stock is estimated in the range of 0.5 – 5% by Fisk et al. [85] based on their review of the literature and previous research, where the improvement was found to be between 2 – 20%. However, a factor of two was applied assuming that only half the people’s activity is affected by the change in IEQ and another factor of two was applied assuming that in research the variations made in parameters are twice as large as likely to be made.

An experiment was conducted by Lan et al. [86] with twelve volunteers and monitored air-temperature, operative temperature, relative humidity, CO₂, ventilation rate, light intensity and noise. Based on the findings, a relationship between relative performance and thermal sensation votes was proposed as below:
\begin{equation}
RP = -0.0351 tsv^3 - 0.529 tsv^2 - 0.215 tsv + 99.865
\end{equation}

where \(RP\) = relative performance compared to maximum performance; \(tsv\) = thermal sensation vote (-3 to +3).

A direct relation was also established by Roelfsen between the Predicted Mean Vote (PMV) and productivity loss [87]. The relationship was derived based on the models proposed by Fanger [36].

\begin{equation}
P = b_0 + b_1 PMV + b_2 PMV^2 + b_3 PMV^3 + b_4 PMV^4 + b_5 PMV^5 + b_6 PMV^6
\end{equation}

where \(P\) = loss of productivity or performance (%) (\(P\geq0\)); \(b_0-b_6\) = regression coefficients.

Linkages between environmental conditions and job satisfaction have also been identified in a study of 95 occupants (workstations) at an open-plan office building [88]. However, a recent study of 167 new or recently retrofitted (<10yrs) office buildings in 8 European countries (Finland, France, Greece, Hungary, Italy, The Netherlands, Portugal and Spain) found that the highest satisfaction rating was given to lighting comfort followed by thermal comfort, noise and air quality [55]. Research on non-retrofitted schools in Portugal by Almeida et al. [89] identified insufficient comfort and IAQ conditions. An indoor average air temperature of 14.6°C and low ventilation rates accounted for poor IEQ in those schools. The popular components that were studied in literature were temperature, ventilation and their combined effects, and CO\(_2\) levels, therefore, these are discussed in detail in the next sections with respect to their effect on productivity.

\subsection{2.4.1 Indoor air temperature}

A few studies have attempted to investigate the relationship of the indoor air temperature and performance of the occupants emphasising the relationship of temperature to mental and light manual work. Based on statistical and quantitative relationships, Fisk et al. [90] demonstrated the link between temperature and work performance. They validated their results based on a few field and experimental studies. Based on the meta-analysis of 24 studies, the authors
derived the following equation, where it gives an estimate of how office work performance varies with temperature [91]:

\[ RP(\%) = 0.1647524 \times T_c - 0.0058247 \times T_c^2 - 0.0000623 \times T_c^3 - 0.4685328 \]  \hspace{1cm} (2.15)

where \( RP = \) the relative performance (compared to the maximum value); \( T_c = \) room temperature (°C). This equation is not applicable for temperature below 15°C and above 32°C.

Their findings, as shown in Figure 2.6, highlight that occupants’ performance improved when the indoor air temperature has an upper limit to 21-22°C and it decreased when the temperature is above 22-23°C. The overall performance of occupants may vary with changing indoor air temperatures. Setting up of optimum thermostat settings would improve the occupants’ comfort in their work environments of non-domestic buildings. An observational study conducted in a call centre office environment showed that productivity can fall by 5-7% due to elevated indoor air temperatures above 25°C [84]. Similarly, at a lower temperature below 20°C the productivity was observed to be reduced [86]. Hence, it can be derived that overheating may lead to a fall in productivity and lower temperatures also affect productivity negatively. Indoor air temperature limits form a crucial part of IEQ and must not be ignored while retrofitting existing buildings. The applicability of the developed metric (relative performance) is not yet evaluated extensively in other real environments and presents a significant gap.

Figure 2.6 Relationship of office work performance and indoor temperature based on the study results [91]
2.4.2 Ventilation rate

The outdoor ventilation rates vary considerably in different zones of buildings and depend on the fresh air requirements for that zone. Ventilation rate impacts the indoor air quality in terms of concentration of indoor airborne pollutants and CO$_2$ [92]. It also affects thermal comfort and indoor humidity levels. Poor indoor air quality can reduce work performance in offices by 6-9% and, hence, can incur significant cost impacts on organisations [93]. Seppanen et al. [94] studied the impact of ventilation on work performance in the office through site and laboratory experiments. The methods were similarly employed to find out the relationship of the temperature to the work performance as in equation (2.15). The relationship is given below:

$$RP(\%) = \exp\left(\frac{-76.38X^{-1}0.78X \ln(X) + 3.87X - y_0}{1000}\right)$$ (2.16)

where $X$ is new ventilation rate in L/s per person (range between 6.5L/s – 47L/s) and

$$y_0 = -76.38X^{-1} - 0.78X \ln(X) + 3.87X$$ (2.17)

The above equations were derived based on nine studies and it was demonstrated that predicted performance was improved by an increase in ventilation rate, as shown in Figure 2.7.

![Figure 2.7 Various ventilation rates and relative performance of employees in offices](image)

A simplification derivation of equations 2.16 and 2.17 is given below [80]:

53
\[ RP (\%) = 0.021 \ln Q + 0.960 \]  

5 l/s per person \( \leq Q \leq 45 \) l/s per person

### 2.4.3 Combined effect of indoor temperature and ventilation

The previous two sections discussed the empirical relationships of productivity with air temperature and ventilation. The combined effect of air temperature and ventilation was studied by Wargocki et al. [78] to derive the relative performance of occupants of a building. It was proposed that the magnitude of the combined effect is least equal to that of the parameter with the highest value, but not more than the sum of both parameters. Dai et al. [17] proposed an equation for overall relative performance based on

\[ RP_H = \frac{1}{2} x (RP_H + RP_L) = 1 + \frac{1}{2} x [\alpha_1 + \alpha_2 + \max (\alpha_1, \alpha_2)] = \frac{1}{2} x [RP_t + RP_q + \max (RP_t, RP_q) - 1] \]  

Referring to Figure 2.8, the horizontal axis represents the indoor air temperature and the vertical axis represents the outdoor ventilation rate. \( t_o \) and \( q_o \) represent the poorest work performance values. \( \alpha_1 \) and \( \alpha_2 \) are the change in relative performance when the indoor environment improves with coordinates.

Figure 2.8, representing \( RP_H \) as relative performance and \( RP_L \) as the effect of largest value either from air temperature or outdoor ventilation:

Referring to Figure 2.8, the horizontal axis represents the indoor air temperature and the vertical axis represents the outdoor ventilation rate. \( t_o \) and \( q_o \) represent the poorest work performance values. \( \alpha_1 \) and \( \alpha_2 \) are the change in relative performance when the indoor environment improves with coordinates.

Figure 2.8 Relative performance to air temperature and ventilation rate [91]

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2.4.4 Impact of CO$_2$ levels on productivity

CO$_2$ is used as one of the metrics to measure the ventilation rate. It has been co-related with the indoor airborne pollutants, contaminants and allergens. Evidence from literature highlight that improvement of CO$_2$ levels can be strongly linked with ventilation rates and bio-effluents, thus improving the indoor air quality, as discussed in Section 2.3.4. CO$_2$ levels and their impact on humans have been studied in relation to the health and perceived air quality [71]. Although indoor CO$_2$ is not a pollutant, its levels are often considered a surrogate of ventilation rates per occupant. Estimation of the impact on work productivity due to different ventilation rates have been outlined in Section 2.4.2. ASHRAE standard 62 outlines a maximum of 700ppm above the outdoor CO$_2$ levels for office buildings [95], whereas the recommended indoor CO$_2$ level in EN15251 is 800ppm for existing buildings above outdoor levels [26]. The influence of high (1000-2500ppm) CO$_2$ levels on cognitive abilities of occupants have been identified through research and it was found to have a significant impact on the decision-making and performance [96], [97]. Evaluation of CO$_2$ levels in existing buildings to be retrofitted offer an opportunity to improve productivity and health benefits.

Since there are a number of parameters (e.g. temperature, ventilation rate, CO$_2$, noise level etc.) involved in the estimation of the IEQ in buildings, their interaction adds to the complexity of evaluation for overall comfort in buildings and thus largely this area is understudied especially for existing buildings. Thus, this research largely focused on examining the impact of retrofit on IEQ parameters and evaluating its effects on occupant satisfaction in the field-study building in Chapter 4. Several gaps were identified such as lack of longitudinal studies, inconsistency in metrics for measuring productivity and absence of technologies for measurement. Therefore, investigation of the impact IEQ on productivity forms a part of future work due to its wider scope in Chapter 7. However, a brief insight of its relevance is presented in practical implications in Chapter 7.

2.5 Whole Building Energy Models

Whole building energy modelling or analysis tools are generally classified into two main categories: (1) inverse modelling and (2) forward modelling [98]. In the inverse modelling approach, the energy analysis model is used to deduce the building characteristics such as load coefficients, base load and time constant. This approach is simpler and uses existing weather
data, energy consumption data, and other performance data to do inverse calculations. On the other hand, the forward modelling approach is a commonly used approach that uses the building characteristics such as construction properties, geometry, schedules and HVAC details for generating the model to predict the final energy consumption. This is the most popular approach and existing software such as DOE-2, EnergyPlus, TRNSYS, IES-VE follow this approach. Figure 2.9 and Figure 2.10 show each of these approaches.

![Inverse modelling approach](image)

*Figure 2.9 Inverse modelling approach [98]*

![Forward modelling approach](image)

*Figure 2.10 Forward modelling approach [98]*

The existing energy simulation tools can use either steady-state or dynamic modelling approaches. In steady-state conditions, the models are not time dependent and can be used for a simpler calculation like energy consumption of a building. However, the dynamic models are time dependent and generate outputs that have the effect of time such as thermal inertia throughout the day, effect of lighting and changing wind. Therefore, in this research dynamic simulation is preferred using EnergyPlus (discussed in the next section) to take into account the real scenario and reduce the risk in outputs.

### 2.5.1 Building energy simulation tools

Nowadays, several building simulation tools are available to conduct detailed analysis of new and existing buildings. These tools are capable of predicting nearly every scenario such as energy consumption, daylighting, Life-Cycle Costs (LCC), indoor pollutant concentration, heat losses, heat gains and others [99]. These simulation tools model the existing building using the construction data of the building such as geometry, building components (wall, roof, floor,
windows), schedules (occupancy, operation, lighting, equipment), loads (occupancy, lighting, equipment), HVAC systems, renewable energy systems and electrical energy systems. These tools require a higher understanding of building physics and expertise in understanding the complexities and inter-relationships in buildings. There are several popular simulation tools being used in the industry and research, such as BLAST, DOE-2, e-Quest, EnergyPlus, IDA-ICE, ESP-r, IES and TRNSYS. The contrasting capabilities of the energy simulation software were mapped by Crawley et al [100] and a comparison of some of them are given in Table 2.3.

<table>
<thead>
<tr>
<th>General modelling features</th>
<th>EnergyPlus</th>
<th>ESP-r</th>
<th>IDA-ICE</th>
<th>IES</th>
<th>TRNSYS</th>
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</thead>
<tbody>
<tr>
<td>Simulation solution</td>
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<tr>
<td>Simulation of loads, systems and solutions</td>
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<tr>
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<td>Variable time intervals per zone for interaction of the HVAC system</td>
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<td>Simultaneous selection of building systems and user</td>
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<td>Dynamic variables based in transient solutions</td>
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<td>Export Geometry of Buildings for CAD software</td>
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<td>Import/ Export of simulation models for programs</td>
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<td>Calculation of thermal balance</td>
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<td>Absorption/ release of moisture from building materials</td>
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<td>Airflow through the windows</td>
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<td>Heat transfer from the soil</td>
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<td>Daylighting and lighting controls</td>
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<td>Infiltration of a zone</td>
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<td>Automatic calculation of coefficients of wind pressure</td>
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Most of these building simulation tools can comprehensively model a range of conditions and the choice completely depends on the user and their requirements. EnergyPlus [101] has been developed over two decades. It is a comprehensive software and being used in the industry through platforms such as OpenStudio [102] and DesignBuilder. In a review by Lee et al. [103], of 18 energy retrofit toolkits that are freely accessible, 9 of them used EnergyPlus as their simulation engine, 2 used DOE-2 and only one used e-Quest. The remaining were based on empirical data-driven and normative methods, highlighting the popularity of the EnergyPlus simulation engine. EnergyPlus software/engine has been utilised for several energy retrofit studies of educational buildings, where the investigation aimed at reliable modelling combined with multi-objective optimisation to determine energy conservation measures (ECMs) for achieving low and near zero-energy standards [104], [105]. EnergyPlus is a robust and strongly recommended tool within the research sector and it is capable of handling complexities in the model due to the possibility of detailed inputs required [101], [105], [106]. Thus, it will be utilised in this study in Chapter 5 and 6.
2.5.2 Uncertainty analysis

Building energy modelling is susceptible to the different uncertainties that exist in the inputs. These tools work with the basic assumption of ‘garbage in- garbage out’; therefore, it is essential to conduct uncertainty analysis in order to develop reliable building energy models. There are certain basic factors that contribute to uncertainty in Building Energy Model (BEM) predictions [107] i.e. (i) occupant behaviour, (ii) impact of climate, (iii) changes due to operation and maintenance, (iv) alterations in indoor environmental conditions, (v) internal heat gains and (vi) building equipment. Currently, there are no standard frameworks to address uncertainty in BEM [108]. A range of sources of uncertainty was determined by Heo et al. [109] while carrying out energy retrofit analysis, such as scenario uncertainty, building operation uncertainty, model inadequacy and observation error.

There are varied sources of uncertainty in building model calibration and they must be identified to address them through different analyses such as uncertainty and sensitivity analysis. The two tasks are often coupled in a generic term ‘sensitivity analyses’. Sensitivity analysis is often a pre-requisite to a calibration process [110]. There are several ways in which the analysis can be conducted depending on the requirements, such as single vs multiple parameters [111]. Sensitivity analysis methods can be classified into local methods (computationally fast and reduced space for the input factor around a base case) and global methods (regression, screen, variance based and meta-model that examine the influence of an uncertain parameter over whole parameter range) [112]. Local sensitivity is defined as the sensitivity of the objective output to changes in one input parameter holding all other input parameters fixed, while global sensitivity evaluates the effects on the objective output of all the changing input parameters acting simultaneously over their ranges of uncertainty. The choice of methods depends on several factors such as time, cost, research purpose, the familiarity with methods and number of input variables. Local sensitivity analysis has been used previously by Petersen and Svendsen [113] with BEM to provide building designers an overview of the impact by adjusting a focus parameter on indoor environment and energy performance prior to building construction. Global sensitivity analysis methods are popularly known as screening based methods that identify the least important input and can be fixed without effecting the output in building energy simulation [114].
Based on the advantages of global sensitivity analysis methods, this research adopted a screening method (Morris method \[115\]) being computationally fast, low-cost and capability to handle large set of input parameters. Further details regarding sensitivity analysis are provided in Chapter 5.

### 2.5.3 Model calibration

The building energy model (BEM) calibration is a ‘manual, iterative and pragmatic intervention’ \[116\]. It can also be based on special test and analytical methods/ procedures. BEM calibration has been referred to as an over parameterised process that has immense interdependencies with input variables representing the complexity of building systems \[107\]. Several studies have demonstrated methods of calibration of BEM models \[117\]–\[119\]. Graphical techniques have also been used to calibrate the models by visualization of results between simulated and actual data \[120\]. Calibration is generally conducted after uncertainty analysis, where the sensitive parameters are identified and used to tune the model during the calibration process. There are certain risks involved in calibration that can be reduced through recommendations such as; (a) using hourly measured data as the target function for the calibration, (b) tightening the acceptance criteria, (c) reducing the amplitude of the parameter space through visual inspection and walk-through audits, (d) calibrating against more than one outcome variable, (e) combining more acceptance criteria to a single goodness-of-fit indicator, and (f) using a small number of calibrated models rather than one single model to obtain robust predictions of the energy and demand reductions \[106\]. Fabrizio et al. \[121\] classified five different levels of information required for the calibration of BEM. Level 1 is the basic calibration level without any details of building operation and uses only basic as-built and utility data. Level 2 approach requires site verification using as built data. Level 3 is based on detailed audit and spot measurements in addition to previous levels. Level 4 requires detailed building audit with short-term monitoring and Level 5 is the most detailed where long-term data is required in addition to the last four levels.

Studies have indicated that empirical model calibration methods can reduce the gap between the actual and simulated data patterns and improve its feasibility \[122\]. One of the most significant parameters that could affect the prediction of energy consumption of the building energy model is the accuracy of occupancy data and plug loads \[123\]. These parameters should be the first factor to be adjusted by inverse modelling based on measured data in model
calibration, which is generally opposite to the traditional method described in the standards to start calibration with energy utility bills or data [110]. There are a lot of research on building energy model calibration, yet it is not effectively developed for the purpose of retrofit applications of existing buildings and they do not offer an effective methodology for calibration [103]. This research considered developing a novel calibration methodology to achieve higher accuracy in energy modelling in Chapter 5.

Geometrical and thermo-physical characteristics have to be defined for a building model in a BEM software for simulation of energy performance, which works on transient relationships of heat transfer [124]. This provided additional motivation to develop BEM in Chapter 5 using EnergyPlus software for the prediction of energy performance. Retrofitting of existing buildings is challenging given the complexity of the relationships between its condition, use, and systems [125]. Therefore, the relevance of calibrated models in the retrofit analysis for decision making is highlighted by Heo et al. [126]. Building energy models must be calibrated, but the extent to which they can be calibrated is dependent on the available data and details.

2.6 Retrofit strategies

2.6.1 Integrated approach in retrofits

Integrated strategies for retrofits requires the building to be considered as an integrated system with the objective to reduce energy consumption, improve comfort, and environment friendly (reduced GHG emissions), while being cost-effective (LCC) [127]. Recently, whole building energy modelling is being used in the comprehensive evaluation of integrated building energy retrofits of existing buildings. However, integrated strategies are becoming increasingly popular in retrofits where low-energy systems are combined with renewable systems to reduce the energy demand. Passive design techniques are being used along with active systems to minimise the loads. Several envelope retrofitting strategies can be combined with building systems such as PV integrated facades to achieve cost-optimality, save energy and improve existing envelopes. Current regulations demand from the member states to achieve nZEB performance in existing buildings through retrofits aimed at bringing environmental, economic, social and health benefits [128]. Achieving nZEB performance is possible through the use of integrated strategies in the retrofit interventions [129].

Retrofit interventions can be classified into three major categories:

i. Load reduction measures,
ii. Renewable building systems and services,

iii. Building envelope, and

iv. Operation and behaviour.

Synergies between them can be identified and used as a combined strategy. Table 2.4 lists a few examples of retrofitting strategies being used in the industry.

*Table 2.4 Summary of retrofit categories*

<table>
<thead>
<tr>
<th>Retrofit measures</th>
<th>Descriptions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Renewable energy systems</strong></td>
<td></td>
</tr>
<tr>
<td>Photovoltaic</td>
<td>BIPV (Building Integrated Photovoltaics) combined with solar collectors</td>
</tr>
<tr>
<td></td>
<td>Trombe walls integrated with PV</td>
</tr>
<tr>
<td>Wind turbines</td>
<td>Micro-wind turbines</td>
</tr>
<tr>
<td>Solar hot water</td>
<td>Combined with PV</td>
</tr>
<tr>
<td>Biomass boiler</td>
<td>Low emissions and clean power</td>
</tr>
<tr>
<td><strong>Heat recovery</strong></td>
<td></td>
</tr>
<tr>
<td>Combined heat and power (micro-CHP)</td>
<td>Electrical power and heat with low emissions</td>
</tr>
<tr>
<td>Geo-thermal heat pump</td>
<td>Closed loop GHP</td>
</tr>
<tr>
<td>Heat recovery ventilation systems</td>
<td>Combined with façade systems</td>
</tr>
<tr>
<td><strong>Optimal control</strong></td>
<td></td>
</tr>
<tr>
<td>Energy management systems</td>
<td>BMS (Building Management Systems)</td>
</tr>
<tr>
<td>Thermostats</td>
<td>Room thermostats, TRVs</td>
</tr>
<tr>
<td>Occupancy based systems</td>
<td>Room thermostats, occupancy sensors</td>
</tr>
<tr>
<td><strong>Efficient systems</strong></td>
<td></td>
</tr>
<tr>
<td>Energy efficient lighting</td>
<td>LEDs, and low energy consuming lighting</td>
</tr>
<tr>
<td>Energy efficient equipment</td>
<td>Low energy consuming appliances</td>
</tr>
<tr>
<td>HVAC</td>
<td>Passive solar heating and cooling</td>
</tr>
<tr>
<td><strong>Building envelope</strong></td>
<td></td>
</tr>
<tr>
<td>Façade development</td>
<td>Curtain wall systems (advanced)</td>
</tr>
<tr>
<td></td>
<td>Green façades</td>
</tr>
<tr>
<td></td>
<td>WWR, wall reflectance (paints, coatings)</td>
</tr>
<tr>
<td></td>
<td>Natural lighting improvement</td>
</tr>
<tr>
<td>Windows</td>
<td>Triple/double glazed (low-e coating)</td>
</tr>
<tr>
<td></td>
<td>Electro-chromatic glazing</td>
</tr>
<tr>
<td></td>
<td>Phase Change Materials (PCMs)</td>
</tr>
<tr>
<td>Air-tightness</td>
<td>Seals and gaskets</td>
</tr>
<tr>
<td>Ventilation</td>
<td>Hybrid ventilation</td>
</tr>
<tr>
<td>External/internal shading</td>
<td>Smart shading devices</td>
</tr>
<tr>
<td>External/internal insulation</td>
<td>Use of Aerogel</td>
</tr>
<tr>
<td></td>
<td>Vacuum insulated panels (VIP)</td>
</tr>
<tr>
<td></td>
<td>Phase Change Materials (PCMs)</td>
</tr>
<tr>
<td><strong>User behaviour</strong></td>
<td></td>
</tr>
<tr>
<td>Adjusting setpoints and setbacks</td>
<td>Reduce overheating and re-setting preferences and times</td>
</tr>
<tr>
<td>Windows operation</td>
<td>Air-exchange to improve indoor conditions</td>
</tr>
</tbody>
</table>
Integrated approaches are commonly used for new buildings, but they are still not common for when retrofitting existing buildings. Attempts are being made to develop integrated approaches for retrofit projects using simulation tools [130]. Integrated approaches are suitable where ‘deep-retrofit’ are considered as a medium to significantly increase the performance of existing buildings. The meaning of deep-retrofit is explained further in the next sections, but before that the general practice of partial or shallow retrofit is discussed.

2.6.1.1 Partiai-retrofits
A general attempt in building retrofits is the selective fixation of a problem or system (e.g. draught stripping and attic insulation etc.) and may be known as ad-hoc, partial or shallow retrofits. These kinds of partial retrofits generally address the ‘low hanging fruit’ and focus on low cost single measures [130] and are not well analysed for their long-term impact and highlight low carbon emission and energy saving potential [131]. Partial retrofits are generally most cost-effective and creates low-disruption; therefore, they are preferred by owners [132]. However, such approaches will fail to deliver the objectives of energy and carbon reduction or improved comfort in the long-term [130]. If the buildings in the EU are partially retrofitted then they would be required to be retrofitted multiple times, thus greater percentage of stock would be retrofitted in each decade [131]. To achieve the 2050 decarbonisation goals set by the EU, deep-retrofits are required leading to higher energy reductions [133], [134] and these are discussed in this section. It is argued that shallow retrofits may have an impact on energy consumption by 30-50%, but further opportunity for reduction remains untapped [135]. However, not enough evidence is available in literature regarding impact of partial retrofit on IEQ in the retrofitted buildings.

2.6.1.2 Deep-retrofits
Generally deep-retrofit aim at the deepest reduction in the energy consumption of the building. The definition of deep-retrofit is understood variably in the EU and the US. In European definitions, deep-retrofit commonly implies a reduction in the final energy consumption by a magnitude of 75% (heating, cooling, ventilation and hot water) post-retrofit, whereas in the US it is generally understood as the reduction in the range of 30-50% (including plug-loads) [136], [137]. Deep-retrofits are not only identified to bring energy savings but also presents an opportunity to impact the overall IEQ in buildings [138]. The revised EPBD directive in 2018 directed the EU member states to develop deep-retrofit initiatives using long-term strategies based on single and staged retrofit approaches towards achieving nZEB performance [133].
However, the researchers have previously stressed the need of having more data to guide deep-retrofits [139]. Staged retrofit approach have been tested through Building Renovation Passports (BRP) that outline the long-term (15-20 yrs.) approach for complete retrofit of domestic buildings [140], but their feasibility for non-domestic buildings largely remains unclear. This research highlights this gap in Chapter 6 and attempts to identify the impacts of staged retrofit on non-domestic building towards achieving ZEB performance.

It has also been observed that among all the building components, building envelopes are a critical part of deep-retrofits [141], [142]. The retrofit of the building envelope yields maximum environmental benefits with less cost investment, as compared to other systems and sub-systems of the buildings [143]. Zuhaib et al. [144] identified the key areas of progress in retrofitting building envelopes to address the challenges in improving existing building conditions in the EU. Building envelopes have been identified to have the highest impact on improving the existing building performance and indoor conditions [129], [145]. Also, upgrades to the building envelope are considered a critical element to reach the 2050 decarbonisation goals in both the US and Europe. According to the United States’ DoE (Department of Energy) estimation, building envelope impacts 57% of the building thermal loads [146]. A list of barriers and challenges was introduced under a multi-annual roadmap to 2020 by the European Commission for energy efficient buildings concerning envelope performance that has gained much importance after the result of past retrofit and renovation activities [21].

2.6.2 Building envelope retrofits

Building envelopes are developed in different building contexts to improve architectural quality and forms a major part of deep-retrofits [139], [147]. The design of envelopes depends on many factors, such as external and internal environmental conditions, thermal performance requirements and users’ satisfaction [148]. Therefore, it is necessary to enhance the role of building envelopes for their overall impact on indoor environmental quality and energy performance of buildings. The performance of an envelope largely depends on its physical properties integrated with the building as a whole [149]. Focusing on the old and existing building stock in Europe, the majority of opportunities are with the retrofit of building envelopes due to their large contribution to energy consumption as discussed in the previous section. Improvement of envelopes will impact the thermal, visual and acoustical needs of the
occupants and also contribute to energy reduction. A general framework with an integrated approach was developed by Martinez et al. [150]. It explains the assessment criteria for envelope retrofit (façade), which entails high levels of association to factors like climate, orientation, durability and code compliance. Also, the integration of ‘soft benefits’ is explored like human comfort, urban regeneration, corporate image and historical value. The role of retrofitting building envelopes is widely recognised for its impact on reducing operational energy in existing buildings, but it also offers an opportunity to impact ecological, urban, social, and economic issues related to the building [150], [151]. Based on the above findings retrofit measures towards improving building envelope were proposed for deep-retrofit in Chapter 6.

It is useful to note that recent developments in the digital age have provided new computational tools to design and optimise buildings using parametric design and genetic algorithms [152]. However, despite the advancement in new techniques and integration between the design and performance (for example, [153], [154]), self-sufficient tools are lacking that effectively aid in developing deep-retrofits. Generally, a combination of building modelling tool, energy performance simulation tool and optimisation tool is required for assessment of retrofit packages [155], [156]. More examples of such combination of tools is presented in the next section. Owing to the lack of comprehensive tools, a similar approach is adopted in this research by coupling different tools in Chapter 6 for retrofit analysis.

2.6.3 Optimisation in retrofits for decision-making

Optimisation is generally defined as a study of the objectives that must be minimised or maximized; it is a function of some variables and it is recognised as central to decision-making in engineering and economics [157]. The optimisation is being used in retrofit research as an effective technique for decision-making to determine of the best set of variables that address multiple-objectives for an existing building, such as reduction in heating energy consumption, improvement in thermal comfort and improvement in ventilation. Due to the complexity in interacting variables in building performance, optimisation approaches are being pro-actively used in both research and industry to analysis retrofit measures. Optimisation relies heavily on computation capabilities. Optimisation problems are classified based on the nature of design variables, types of constraints and number of objective functions. There are several optimisation algorithms and methods that are available, and their choice depends on the nature
of the problem to be solved. The optimisation problems in retrofit are generally classified as single-objective or multi-objective problems and these are elaborated in the next sections.

2.6.3.1 **Single-objective optimisation**

Single objective optimisation focuses on single objectives with one or more variables defined within the same function. The main goal of single-objective optimisation is to find the best solution that corresponds to the minimum or maximum of the objectives combined together in single function [158]. Single objective optimisation techniques are classified in three major categories i.e. (i) Calculus (numerical) based techniques, (ii) Enumerative techniques, and (iii) Guided random techniques [159]. Figure 2.11 shows the different search and optimisation techniques under three main categories. In calculus-based techniques, a set of numerical conditions are to be satisfied through the solution within the optimisation problem. The scope of numerical based optimisation techniques is very limited due to their nature of local search and derivative assumptions. The enumerative techniques arrive at the solution by evaluation all the points of finite search space. An example of the enumerative technique is dynamic programming. Guided search techniques are derived using enumerative methods but use additional information to explore the search space. These search techniques are divided into single and multiple point search and are meant to deal with the large sample or search spaces where the near optimal solution is also acceptable. Some examples of random techniques are simulated annealing, ant colony optimisation, genetic algorithms and tabu search.

![Figure 2.11 Search and optimisation techniques](159)
2.6.3.2 Multi-objective optimisation (MOO)

When there is more than one criterion that must be decided to arrive at a solution achieving the optimised result of all the criteria is known as multi-objective optimisation. The multi-objective optimisation has numerous applications in real-world problems and is being used in retrofitting applications and analysis throughout the research. It is very common to analyse the multi-objective optimisation problem thorough the concept of domination (pareto optimality). In pareto optimality, a set of multiple solutions are identified, as in Figure 2.12 for a two-objective optimisation problem. A solution of a two-objective optimisation problem yields 5 solutions and it can be said that solution 1 is dominated by solution 4 and 5. This type of pareto frontier allows the comparison of the different solutions in multi-objective optimisation problems.

![Figure 2.12 Pareto frontier and dominance of solutions](image)

Multi-objective optimisation problems can be solved using several techniques such as NSGA-II [160] and strength pareto evolutionary algorithm (SPEA) [161]. Genetic algorithm (GA) is a population-based algorithm and widely applied to solve multi-objective optimisation problems. Figure 2.13 shows the steps used in the Genetic Algorithm. GAs are an adaptation of natural methods of selection into computational procedures. The parameters of the search space are encoded in GAs in structures known as chromosomes (or strings). The algorithms iteratively execute on a set of chromosomes known as population, along with the three basic operators: selection or reproduction, crossover, and mutation.
A summary of several optimisation studies on retrofitting options for buildings contained in the literature that use multi-objective optimisation is given in Table 2.5, where the tools and techniques used for the optimisation are outlined, together with the objective functions and variables. Multi-objective optimisation using genetic algorithm (GA) is a much-implemented approach by building researchers in retrofit due to its high benefits and intervention measures targeting more than one objective function. Since deep-retrofit is a multi-objective problem, this research considered the used of multi-objective optimisation using genetic algorithm in Chapter 6.

An appropriate selection of retrofit strategies for optimising building envelope insulation in EDSL Tas (a response factor based simulation tool) was done through a calibrated simulation approach resulting 14.55% reduction in energy savings [170]. Caldas et al. [172] conducted optimisation using GA for optimum insulation thickness through Pareto based approach achieving 41% saving in cost and also optimised the building form with the trade-off being lighting and heating energy. Usually, BPS requires high computation time; therefore, Lartige et al. [173] produced a methodology for optimising the thermo-physical properties of external...
walls employing artificial neural network (ANN) and GA (NSGA-II) reducing the computational time.

**Table 2.5 Summary of examples using optimisation techniques in retrofitting**

<table>
<thead>
<tr>
<th>Reference</th>
<th>Simulation tool/optimisation program</th>
<th>Objective functions</th>
<th>Variables</th>
<th>Building type</th>
<th>Optimisation technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>[162]</td>
<td>TRNSYS, GenOpt, MATLAB</td>
<td>(i) Total annual heating and cooling energy (ii) Life Cycle Cost</td>
<td>External wall insulation, window type, solar collector type, roof insulation</td>
<td>Residence</td>
<td>MOO, Tchebycheff programming</td>
</tr>
<tr>
<td>[163]</td>
<td>TRNSYS, DAYSIM, RADIANCE, GenOpt</td>
<td>(i) Annual heating &amp; cooling load (ii) Daylight</td>
<td>WWR, VT (visible transmittance), ST (solar transmittance), U-value</td>
<td>Dormitory</td>
<td>MOO, Pareto based analysis, Parametric study</td>
</tr>
<tr>
<td>[164]</td>
<td>OPTISOL</td>
<td>(i) Total heating and cooling load (ii) Life Cycle Cost</td>
<td>U-values (wall, window), GR (glazing ratio), SF (solar factor), AT (air tightness), daylight, U-value (roof)</td>
<td>School</td>
<td>MOO, GA, scenario based</td>
</tr>
<tr>
<td>[165]</td>
<td>EnergyPlus</td>
<td>(i) Total heating and cooling energy (ii) Life Cycle Cost</td>
<td>Glazing area, U-value (wall, window), HVAC system, PV, Solar hot water</td>
<td>Modular building</td>
<td>GA (Genetic Algorithm) with local search</td>
</tr>
<tr>
<td>[166]</td>
<td>Statistical model</td>
<td>(i) Energy savings (ii) NPV (Net Present Value)</td>
<td>U-value (glazing, roof insulation, HVAC system, lighting)</td>
<td>Typical model</td>
<td>MOO, GA</td>
</tr>
<tr>
<td>[167]</td>
<td>EnergyPlus</td>
<td>(i) Primary Energy Consumption (ii) Discomfort Hours (iii) Global Costs</td>
<td>Low solar absorptance (roof plaster, external wall), Insulation (roof, wall), U-value (glazing), HVAC systems, PV</td>
<td>Office building</td>
<td>MOO, ANN (Artificial Neural Networks)</td>
</tr>
<tr>
<td>[168]</td>
<td>QFD based tool, VBA for Microsoft Excel</td>
<td>(i) Operational costs (ii) Annual GWP (iii) Investment cost</td>
<td>Insulation (external wall, roof, ceiling), U-value (glazing), heating system, building airtightness</td>
<td>Office building</td>
<td>MOO, GA</td>
</tr>
<tr>
<td>[170]</td>
<td>EDSL Tas</td>
<td>(i) Annual energy consumption (ii) Payback (iii) Carbon emissions</td>
<td>U-values (external wall, interior wall, floor, roof and glazing)</td>
<td>Office building</td>
<td>Sensitivity of ECMs</td>
</tr>
<tr>
<td>[171]</td>
<td>MATLAB, TRNSYS II</td>
<td>(i) Total energy consumption (ii) Net Present Value (iii) Weighted discomfort time</td>
<td>Thermal characteristic of insulation and glazing, heating system, mechanical ventilation system</td>
<td>Residential</td>
<td>NSGA-II</td>
</tr>
<tr>
<td>[155]</td>
<td>MultiOpt, TRNSYS</td>
<td>(i) initial investment cost (ii) PPD index (iii) Carbon emissions</td>
<td>External wall type, roof type, ground floor type, intermediate floor type, partition wall type, window type</td>
<td>School building</td>
<td>NSGA-II</td>
</tr>
</tbody>
</table>
Among other studies using optimisation, Ferrara et al. [174] investigated the relationship of variables for a nZEB concept using an iterative input-output process with TRNSYS and GenOpt by running a parametric simulation for various envelope features that yielded 20% energy savings. Trubiano et al. [175] worked on an automated method for the volumetric optimisation of buildings through a combination of four modelling and simulation programs using GA and single objective function for better energy and lighting performance. They used automated scripts run in Rhino and Grasshopper, EnergyPlus, MATLAB and RADIANCE. Karagkouni et al. [176] studied natural ventilation and optimised window openings of a pavilion using the evolutionary method with GA through Fast Fluid Dynamics [177]. Hemsath [178] worked on early stage design energy modelling approach by parametric optimisation of window locations based on interior daylight factor. On the other hand, Hani [179] optimised office building façade using hybrid multidimensional optimisation algorithm with IDA Indoor Climate and Energy 4.5, considering standards for new buildings and renovation resulting in quick selection charts to be used by architects and designers for nZEB levels.

A set of variables were identified to be optimised that spans across the wall, roof, floor insulations, thermal mass, window shapes and sizes, WWR, and other technical building systems and physical properties of envelopes [155], [162], [180]–[182]. Early stage design optimisation tools for nZEB’s have shown multiple possible configurations to increase energy performance [183]–[186].

Life-Cycle Cost (LCC) assessment forms an important basis to evaluate the success of energy retrofits for mass building stock. Few studies indicated that optimisation of envelope for cost and embodied energy in tandem with energy performance can help designers to identify their choices for retrofits [164], [187]–[189].

The optimisation methods as discussed above were used for various variables such thermo-physical properties of windows and construction materials, ventilation systems, heating set-points, renewable systems that are critical to aspects of existing building performance such as thermal, visual or acoustical comfort and energy efficiency. Selection of objective functions and optimisation variables was influenced in Chapter 6 based on the reviewed literature.
### 2.7 Life-Cycle Costs (LCC)

#### 2.7.1 Whole-Life Cost (WLC)

ISO 5686-Part 5 [190] describes in its scope that whole life cost includes all significant and relevant future costs and benefits of an asset throughout its life-cycle while fulfilling the performance requirements. Whereas, life-cycle cost (LCC) is the cost of an asset or its parts through its life cycle while fulfilling the performance requirements.

In the case of retrofits to existing buildings, the use of WLC is more appropriate due to intangible benefits (reputation, functional enhancement, productivity etc.) associated while evaluation of the overall costs throughout its life. However, it is difficult to quantify the intangible benefits and, therefore, LCC is preferred in cost calculations. Design and functionality assessment are two key interest areas for conducting LCC on retrofits. The scope of the costs included or excluded should be appropriately defined with the client and selected based on the project briefs. Figure 2.14 illustrates the elements to be included in WLC and LCC.

![Figure 2.14 Elements of WLC and LCC [191]](image_url)

A detailed flow of whole life costs relevant to retrofits is shown in Figure 2.15. The LCC for retrofits consists of costs of design and construction, operation and maintenance, as well as operational energy. A description of life-cycle costs and formulas is described further in the section.
Figure 2.15: Whole life costs during retrofit
2.7.2 Life-Cycle Costs (LCC)

Life-Cycle Costs (LCC) includes all the capital investment costs and operational costs occurring over different stages of the life of the asset. Non-construction costs, income, externalities and intangibles are included in the calculation of Whole life costs (WLC) along with LCC, as in Figure 2.15, and are specific to the project briefs. Based on the LCC description reported by ISO-15686: Part 5 [190], the following relationship is to be considered in LCC calculations of retrofits.

\[ F_{LCC} = I_C + OMR_C + R_C + O_E + RE_C \]  \hspace{1cm} (2.20)

where \( F_{LCC} \) = life cycle cost of retrofit; \( I_C \) = initial capital construction costs; \( OMR_C \) = operation, maintenance and repair costs; \( R_C \) = replacement costs; \( O_E \) = operational energy costs; \( RE_C \) = residual value (less disposal cost)

2.7.2.1 Data required for LCC calculation

i. Initial capital construction costs

Initial capital costs would include all the project costs (direct and indirect) such as construction costs, professional services, planning fees, demolition, disposal and temporary accommodation of the occupants. The total capital investment during the retrofit is generally based on the industry benchmarks and cost-estimation books. In retrofit projects, along with the main investment for specific tasks for improving the energy performance of the building, general refurbishment upgrades and works are also carried out and included in the initial investment costs.

ii. Operation, maintenance and repair costs

Operation and maintenance are inherent to the LCC analysis and the costs incurred are to ensure that the service life is increased to meet the design life of the building component being repaired or maintained. Additionally, service life prediction is important to include the annually recurring costs in the calculations. With respect to building and constructed assets, service life prediction procedures are presented in detail in ISO 15686-2 [192]. Different components of the building being retrofitted have different service life; therefore, it requires an estimation towards maintenance and repair durations. For example, the annual maintenance plan for a
façade may include internal and external cleaning, sealing of windows, repair of joints and frames, etc.

iii. Residual values
The constructed assets in retrofit projects generally have a residual life at the end of the study period. It is known as the economic value of the building component from the end of the study period to the end of its lifespan. According to ISO 15686-5 [190], the residual values be evaluated by ‘determining what similar, comparably-aged assets in similar locations are selling for in commercial markets', or where this is unavailable a 'straight-line depreciation based on the capital value and depreciation over the service life or design life of the asset’. In the NIST handbook [193], it is suggested to estimate the residual by pro-rating the initial cost based on the remaining useful life of the component. For example, a system with an expected useful life of 10 years that was installed 5 years before the end of the study period, the estimated residual life will be $\frac{1}{2} = \frac{(10-5)}{10}$ of the initial cost.

iv. Operational energy costs
Based on the energy retrofit measures, there are significant energy savings that basically means a reduction in the operational energy and, thus, reduction in operational energy costs. Energy savings are not directly used in the LCC calculation, but first discounted to the present value using the annual energy savings and then used in LCC calculations. The operational energy costs are estimated using building simulation analyses software for annual energy saving based on retrofit measures. These costs are obtained by multiplying the fuel price in €/kWh with the estimated energy savings.

v. Net Present Value (NPV)
During the calculation of LCC, all the future expenditures should be discounted with the Net Present Value (NPV) formulae to a cumulative sum in today’s monetary value [191]. It is necessary to consider all the inflations and discount rates occurring over the different expenditures at different times to bring all cost in present value. NPV is a single figure which considers all relevant future incomes and expenditure over a period of analysis. A study period is selected to evaluate different systems and solutions in the cost calculations.
The relationship of NPV is given below:

\[ Z_{NPV} = \sum(C_n \times q) = \sum_{n=1}^{P} \frac{C_n}{(1+d)^n} \]  

(17)

where \( Z_{NPV} \) is net present value; \( C \) is cost in year \( n \); \( q \) is discount factor; \( d \) is expected real discount rate per annum; \( n \) is number of years the base date and occurrence of the cost; \( p \) is period of analysis.

### 2.7.2.2 Economic parameters for LCC analysis

**i. Study period (period of analysis)**

One of the main inputs to LCC calculations is the duration of the study period. It is normally defined as the period over which the cost and benefits of retrofit measures are analysed, or the investor has interest in the building in investing capital. Longer study periods justify higher initial capital investments. The study period may include the base date of planning or construction and the service period.

**ii. Discount rate**

The discount rate is one of the basic assumptions required for calculation of LCC. It can be defined as a different type of interest that makes the investor indifferent to the cash amounts received at different points in time during the study period [193]. It is also referred to as the quantification of uncertainty coming from the investments in the during the study period in retrofit projects. As per ISO 15686-5, the range of discount rate is typically between 0 to 4% [190]. Generally, for public sector, these values are set by the central government.

**iii. General inflation rate**

The inflation rate refers to an overall increase in the prices of goods in the current month compared to the last year and is generally an index indicating the decline in purchasing power of the currency. The present value calculations are done using the two approaches for inflation i.e. (i) current euro and (ii) constant euro. Current euro refers to the future amounts stated in actual prices as of the year when they are expected to occur. This approach is said to be inclusive of inflation. Whereas, constant euro refers to the uniform purchasing power of the euro in any year excluding inflation, meaning that the same goods or services would cost the same at different times [193].
iv. **Fuel price escalation rate**

Fuel (electricity, natural gas, oil) prices are subject to change with general inflation rates every year. These escalation rates are generally above the general inflation rates and affect fuel prices the most compared to the other commodities and goods. Therefore, in LCC calculations a national fuel price escalation rate is assumed based on the annual trends.

### 2.8 Conclusions

The background study presented in this chapter highlighted some of the major interactions between the research in different domains of building retrofit. The role and relevance of stakeholder analysis is considered crucial in understanding the growing energy efficiency industry effectively and tackle the emerging barriers, gaps and challenges. Several techniques for assessment of IEQ of existing buildings and their computational analysis were studied and presented in the literature review. These are applied in the current research and involve the use of thermal comfort models, metrics for visual comfort analysis, threshold limits for acoustical analysis and IAQ determination. A review of available whole building energy simulation tools enabled the identification of suitable retrofit oriented and flexible building energy simulation tools that could be used in this study, allowing coupling with other third-party applications.

From the review of existing research on uncertainty analysis and calibration techniques, it was identified that a novel methodology was required to achieve calibration building energy model for decision-making on determining the most suitable retrofit solution packages.

Based on the review of previous studies, retrofits must aim to meet more than one performance parameter of the existing buildings using an integrated approach through deep-retrofit. It was identified that partial retrofits are cost effective and bring energy reduction up to 30-50% but limit further reductions, however, their benefits on IEQ are not clear in literature. For achieving higher energy performance and achieving EU energy reduction goals, deep-retrofits are being emphasised due to their ability to reduce energy consumption up to 75%. To tackle financial barriers and achieve nearly zero-energy performance, single stage and staged retrofit are being tested for domestic buildings but their ability to achieve nearly zero-energy performance is not yet tested for non-domestic buildings and it requires further investigation.
Chapter 2. Literature review

An approach to multi-objective optimisation guided the application of multiple deep-retrofit measures and their evaluation based on several objectives. Decision-making support and multi-objective optimisation methodologies offer an opportunity to find the trade-offs and focus on the most imperative solutions within the complex interactions of building performance parameters.

The key gaps identified that are addressed in this research include (i) the relationship of IEQ and energy performance and its quantification for partial building retrofits, (ii) the role of uncertainty in existing building retrofits and the importance of accurate calibration of computer simulations to achieve better performance through building energy models, (iii) developing integrated deep-retrofit strategies and testing them for single and staged approaches and (iv) the application of multi-objective optimisation for decision making with respect to deep-retrofit of existing buildings.

2.9 References

Chapter 2. Literature review


Chapter 2. Literature review


Chapter 2. Literature review


517, 2010.


Chapter 2. Literature review


Chapter 2. Literature review


Chapter 2. Literature review


Chapter 2. Literature review
Chapter 3 : Attitudes and approaches of construction professionals in Irish retrofit industry towards achieving nearly-zero energy buildings

3.1 Chapter overview

This chapter presents a stakeholder investigation conducted among local participants from the Irish retrofit industry between April and October 2015, in order to learn about their knowledge, practices, experiences and expectations towards achieving nZEB. A comprehensive three-tier methodology was formulated comprising of surveys, a workshop and interviews. This research work was divided in three main parts, (i) Surveys - assessing practice and knowledge gaps (90 respondents), (ii) Workshop - stakeholder engagement exercise (85 participants) and (iii) Interviews- an in-depth investigation with regional stakeholders (11 participants). This investigation uncovered the issues that existed in the slow uptake and low-quality energy retrofits in Ireland in the domestic and non-domestic building sectors. The goal of this research was to deepen the understanding of main barriers, gaps and challenges surrounding the retrofit industry. The lessons learned from this study guided further research (presented in the next chapters). The surveys (Appendix A) focussed on general practices, methods, use of technology, implementation and performance of retrofits. Their overall goal was to find the priorities, needs and issues of different stakeholders in retrofit industry, and to identify the opportunities for developing retrofit solutions. A workshop was conducted with stakeholders, after carrying out the surveys, to enquire about their opinions and experiences on governance, health impacts and implementation of retrofits. Feedback from the workshop showed a general concern towards financial structures and banking support for retrofits. Syncing of building regulations with the retrofit requirements was emphasised by the planning authorities. The final step in the stakeholder investigation were semi-structured interviews (Appendix B), conducted to extrapolate contrary approaches and individual attitudes towards low-energy targets.

The findings of the three methods of investigation were triangulated for cross-verification and validation of results. Many similar thoughts were observed from the stakeholders such as the lack of decision-making tools, methods and techniques for retrofit and these were identified as some of the major barriers to achieve nZEBs. There was a dearth of case-studies, post-retrofit data and solutions to improve the performance of non-domestic buildings. Stakeholders also expressed larger concern towards improving the indoor environment that requires coupling with energy efficiency in retrofit projects. The attitudes and approaches of industry stakeholders defined the prospects for the growth of nZEBs and further research.
Chapter 3. Attitudes and approaches of construction professionals in Irish retrofit industry towards achieving nearly-zero energy buildings

This chapter has been published in the *International Journal of Building Pathology and Adaptation* on March 2017. Sheikh Zuhaib designed the study, collected and interpreted the data and prepared the manuscript. The article was co-authored with the primary supervisor Dr. Jamie Goggins who directed this research and commented on the manuscript at all stages. Dr. Richard Manton supported with development of survey and interview questionnaires. Dr. Magdalena Hajdukiewicz and Dr. Marcus Keane advised on the analysis of data from survey, workshop and interviews.

**Abstract**

There is profound demand for higher skills and expertise in retrofitting the existing building stock of Europe. The delivery of low- or nearly zero-energy retrofits is highly dependent on technical expertise, adoption of new materials, methods of construction and innovative technologies. Future Irish national building regulations will adopt the EPBD vision of retrofitting existing buildings to higher energy efficiency standards. The role of key stakeholders in the industry becomes highly responsible for achieving the energy performance targets. Specifically, the paper assesses the attitudes, approaches and experiences of Irish construction professionals regarding energy efficient buildings, particularly nZEBs. Data were collected through a series of assessments under qualitative research including survey, workshop and detailed interviews with professionals in the retrofit industry. The structure of this approach was informed by preliminary data and information available on the Irish construction sector.

There is a substantial amount of ambiguity and reluctance among the professionals in reaching the Irish nearly zero-energy building (nZEB) targets. The growing retrofit industry demonstrates low-quality auditing and pre/post-retrofit analysis. Basic services and depth of retrofits are compromised by project budgets and marginal profits. Unaligned value supply chain, poor interaction among nZEB professionals and fragmented services are deterrents to industry standardisation. This study has implications for understanding the social barriers existing in retrofit projects. Support from clients/owners has a diverse impact on energy performance and retrofit decisions. Community-based initiatives are key to unlock the promotion of nZEBs. This study will enable construction industry stakeholders to make provisions for overcoming the barriers, gaps and challenges identified in the practices of the retrofit projects. It will also inform the formulation of policies that drive retrofit uptake. This paper provides an overview of current activities of retrofit professionals and analyses the barriers, gaps and challenges in the industry.
Chapter 3. Attitudes and approaches of construction professionals in Irish retrofit industry towards achieving nearly-zero energy buildings

3.2 Introduction

The focus of construction in Europe has shifted from new builds to refurbishment to achieve member states’ energy efficiency targets. Indeed, the current rate of refurbishment in Europe is around 1% [1]. A major share of the building stock in Europe is older than 50 years and about 40% of the existing residential buildings were constructed before the 1960s when the building regulations for energy consumption of buildings were limited [2]. In Ireland, residential buildings cover 77.3% of the 234 million m² of total floor area [3] and comprise 27.1% of total energy consumption [4]. During the Celtic Tiger construction boom (1990-2006), floor area increased in the average dwelling by 16.6%, indicating a rising energy demand [5]. More recently, Irish government policies are targeting improvements in the energy efficiency of buildings, particularly in the residential sector. There are immense opportunities in this area for Ireland; for example, the potential primary energy savings of 13.5TWh in the residential sector would represent almost 30% of the total energy demand of 44TWh [6]. The delivery of nearly zero-energy buildings (nZEB) by upgrading existing buildings depends heavily on the policies, practices, and expertise of the construction industry.

UK has imposed a target of 80% reduction in carbon emissions by 2050 [7]. As a result, the sustainable retrofit market for social housing is being upscaled by the government through policy instruments, skill building and improvement of supply chains [8]. A comparative study conducted on Sweden and Norway highlighted the lack of knowledge dissemination between stakeholders in nZEB renovations and how this impacts the decision-making process between the stakeholders [9]. Recent studies indicate that Germany has extensively promoted energy efficiency measures which have created huge benefits for owners, SME’s, environment and economy [10], [11]. This section of the paper outlines the Irish nZEB definition, the existing national framework and policies in place, involvement of the industry and development of the market, and the key role played by nZEB experts.

3.2.1 nZEB definition and Irish government policy

Article 9 of Energy Performance of Buildings Directive (EPBD) directs EU member states to develop nZEB definitions for existing buildings [12]. While 13 jurisdictions have so far identified criteria for existing buildings, only 8 countries (Austria, Cyprus, Czech Republic, Denmark, France, Latvia, Lithuania, and Brussels Capital Region) have established definitions. Ireland has followed these countries by setting up primary energy use requirements for existing
buildings in the draft definition of the national nZEB plan [13]. The nZEB definition of the Department of the Environment, Community and Local Government (DECLG) in Ireland demands an Energy Performance Coefficient of 0.302 and Carbon Performance Coefficient of 0.305 for a typical new-build dwelling with primary energy consumption of 45kWh/m²/yr. However, the target for existing dwellings that will receive significant renovation after 2020 is 75-150 kWh/m²/yr., including space and water heating, lighting and ventilation [14]. As of 2010, the average energy intensity per existing dwelling is equivalent to a D rating (225-300 kWh/m²/yr.) on a BER (Building Energy Rating) scale [15]. For non-residential buildings, an improvement of 50-60% in the energy and carbon performance is proposed.

The Irish government first introduced building energy efficiency requirements in 1991 [16]. Following this, the first performance-based code was introduced in 2002 with the implementation of the EPBD [17]. Current building regulations (Part-L) strengthen national policies with advanced aspects of building energy simulation, U-value requirements, airtightness testing for all new dwellings, bioclimatic design, mandatory renewable energy requirements, and pre-occupancy commissioning with the aim of achieving nZEB by 2020 [18]. The recent release of the Irish government’s third National Energy Efficiency Action Plan (NEEAP III) sets a national target of a 20% reduction in primary energy consumption by 2020, and a 33% reduction in the primary energy consumption of the public sector [19]. A guide to energy efficient retrofits of dwellings (S.R.54:2014) has been developed by the DECLG, the Department of Communications, Energy and Natural Resources (DCENR), the Sustainable Energy Authority of Ireland (SEAI) and the National Standards Authority of Ireland (NSAI) in collaboration with the Building Research Establishment (BRE) [20]. It guides property managers, designers, specifiers and installers on building envelopes, application of retrofit packages, general building science, and management of retrofit projects. Ireland’s energy policy priorities [21] include empowering energy citizens; markets, regulations, and prices; planning and implementing essential energy infrastructures; ensuring a balanced and secure energy mix; putting the energy system on a sustainable pathway; and driving economic opportunity. The efforts from the Irish government follow EU policy for medium and long-term energy-related improvements and they are expected to evolve into strict regulations in Ireland by 2020.
3.2.2 Retrofit industry and construction professionals

Building stock in Ireland was, until recently, amongst the least energy efficient in Northern Europe and new studies indicate a reduction of 4% in household energy consumption since 2008 [22]. This relates to the various energy efficiency measures for renovation and refurbishment taken by the government since the introduction of EPBD and the majority of schemes have been carried out in the residential sector in Ireland. The distribution of energy efficiency measures in the residential sector by the Irish government is based on financial, fiscal, legislative, normative, co-operative, information and education typologies. The residential energy efficiency measures pattern from early 2000 to 2014 suggests the majority of initiatives are legislative, financial and information/education based [23]. The Better Energy Homes scheme (residential retrofit), Low-Carbon Homes scheme and Building Regulations for Nearly Zero-Energy Homes are some of the schemes provided for the residential sector. Measures for the tertiary sector include the action plan for the public sector, the assessment of renewable energy alternatives at the design stage and tax relief for energy-saving equipment.

Market development, adaptability and filling the gaps in homeowner information are of vital importance and are governed by the growing construction industry. The provision of incentives supports the market penetration of nZEBs and a recent market report on Energy Service Companies (ESCOs) in Europe notes that the Irish retrofit industry is growing rapidly due to such incentives [24]. The retrofit industry is an important stakeholder for nZEB and key actors include professionals such as architects, engineers, small and medium businesses, contractors and other construction professionals. For example, Building Energy Rating (BER) assessors are trained professionals who carry out certified home energy audits [25]. Currently, there are 18 dwellings registered with a BER of A1 and 1,549 with a BER of A2 [26]. There have been a few vetted training and certification programmes initiated to produce qualified professionals at operative, craft and supervisory levels in the retrofit industry as shown in Table 3.1. Many initiatives are being taken by the stakeholders for nationally recognized industry credentials to train the skilled labour workforce. A large number of construction professionals still remain untrained in highly energy-efficient buildings and the rapid expansion of building standards in this area has created huge skill gap in the construction workforce.
The level of training and scope of work requires a change in some of the traditional construction practices to achieve energy efficient buildings due to the complexity and demand of nZEB standards. The value supply chain of designers, developers, construction workers, clients and policy makers needs alignment to the current demand of quality and precision for highly efficient buildings. Traditional construction professions, such as carpenters, electricians and builders’ merchants, come into direct contact with the owners and there is a need to identify the value supply chain in the Irish context similar to that presented by Haavik et al. [27] in Figure 3.1. A key component of the Construction 2020 Strategy is the BuildUp Skills roadmap developed by a consortium of government departments, state agencies, training providers and construction workers for upskilling the professionals and tradesmen in retrofit businesses [28].
Chapter 3. Attitudes and approaches of construction professionals in Irish retrofit industry towards achieving nearly-zero energy buildings

Retrofit businesses need consensus over processes, tools and best practices to overcome the existing technical, social, economic and environmental barriers as highlighted in this study. Cohesive interaction among industry stakeholders over project inception, development and delivery standards can raise the quality of retrofits required along with the tools and techniques to achieve them [29]. Several studies have investigated the requirements of end users to assist in decision making in retrofits through the use of surveys [30]–[33]. However, very few studies have evaluated the requirements of construction industry stakeholders in Europe in achieving low energy buildings [34]–[36]. They indicated that most countries require information and training to push market development forward. They also stated that there is lack of trust and reliable information for growth of ESCOs in Europe. Existing skills in the construction sector are of high quality, yet they are not sufficiently aligned with the approach of low-energy building. The ZEBRA 2020 project is trying to develop frameworks for monitoring the market uptake of nZEBs across Europe and its recommendations are awaited [37]; however, it does not include Ireland in its consortium.

Therefore, an extensive stakeholder consultation process was undertaken in this study to identify the barriers, gaps and challenges being faced by the retrofit industry in Ireland. This process, outlined in the following section of the paper, comprises a construction professional survey (Section 3.4.1), a workshop (Section 3.4.2) and in-depth interviews (Section 3.4.3). In
the final section of the paper, the results of each element of the consultation process are synthesised and recommendations for the retrofit industry have been developed.

### 3.3 Methodology

The aim of this investigation is to understand the attitudes and approaches adopted by retrofit industry professionals in their practices or businesses towards delivering or achieving nearly zero-energy buildings. To this end, a three-tier methodology was designed comprising of surveys (90 respondents), a workshop (85 participants) and a series of in-depth interviews (11 participants). The surveys, workshop and interviews were structured into themes to assemble details about the status of the industry and its stakeholders (Table 3.2). This methodology enabled the identification of major barriers, gaps and challenges existing in the retrofit industry in Ireland. A similar research technique was applied to evaluating the Irish industry scenario by a consortium of organisations in Ireland, although it was focussed on the upskilling of industry stakeholders through training [35]. Davies and Osmani [38] also adopted a triangulated approach to evaluating the low-carbon housing refurbishment challenges and incentives. Such use of different methods in data collection ensure consistency, reliability and validity of results [39].

**Table 3.2 Hierarchy of stakeholder engagement and outline of themes**

<table>
<thead>
<tr>
<th>No.</th>
<th>Investigations</th>
<th>Target Audience</th>
<th>Approach</th>
<th>Themes</th>
</tr>
</thead>
</table>
| 1.  | Industry Specific | nZEB experts and actors | Surveys (n = 90) | • Respondents and project characteristics  
• Retrofitting methods  
• Technology and solutions in practice  
• Implementation and performance |
| 2.  | Policy and Regulations, Health and Comfort, State-of-the-art and Impact | All stakeholders | Workshop (n = 85) | • Governance, standardisation, and economics  
• Health, comfort, IAQ, and energy performance  
• Impact of technology and innovation  
• Showcasing best practice |
| 3.  | Envelope/ façade focused | Market players | Interviews (n = 11) | • Experience on envelope retrofits  
• Assessment of design, construction and delivery  
• Use of technology and systems  
• Issues and concerns |
Chapter 3. Attitudes and approaches of construction professionals in Irish retrofit industry towards achieving nearly-zero energy buildings

The Survey (first tier) was targeted towards main nZEB experts and actors of the supply chain who are directly involved in retrofit projects within the industry. A semi-structured online questionnaire was compiled in Google Forms and distributed through email between May and August 2015. The survey was composed of qualitative/open-ended and quantitative questions based on multiple choice, rank order, Likert and rating scales designed to capture the characteristics of individual retrofit businesses. Of the 600 electronic invitations issued, 90 detailed responses were received, giving a response rate of 15%. A purposeful sampling technique was applied to select the respondents from within Ireland [40]. The participants included professionals such as civil/structural engineers registered with Engineers Ireland, architects accredited with the Royal Institute of Architects in Ireland, construction managers, cost consultants, BER assessors (domestic and non-domestic) registered with SEAI, energy consultants, building services engineers and others.

The workshop (second tier) was organised to cross-evaluate the viewpoints, issues and efforts being fluxed in the industry by other stakeholders such as policy makers, planning authorities, NGO’s, SME’s, housing associations, financiers, clients and property owners. The workshop was organised through four themed plenary sessions, as shown in Table 3.2. Invitations were sent out using convenience sampling to other industry stakeholders including the survey respondents, and 85 people attended. The invited speakers outlined their experiences and perspectives on retrofitting in Ireland. Each session was followed by a brainstorming discussion which helped to determine the actions required to strengthen the propagation and effectiveness of energy efficient buildings. Workshops have proven to be a crucial instrument for the design and delivery of National Renovation Strategy for Ireland (v2.0) and an effective implementation plan [41].

The first two tiers of inquiries raised major concerns regarding building envelope/ façade performance. Building envelope forms a crucial component of deep retrofits and is critical in achieving nZEB performance targets [42]. Therefore, the theme of the in-depth open-ended interviews (third tier) was formulated based on envelope/ façade retrofits comprising descriptive and normative questions. A total of 11 experienced market players including architects, civil engineers, cost consultants, BER assessors, manufacturers and construction managers were interviewed with the aim of capturing detailed views of these professionals.
Chapter 3. Attitudes and approaches of construction professionals in Irish retrofit industry towards achieving nearly-zero energy buildings

3.4 Results and discussion

3.4.1 Survey results: Assessing the retrofit practice

The survey was prepared in common for all nZEB experts and actors in consultation with retrofit professionals. The results are summarised and discussed in the following four categories:

1. Respondent and project characteristics
2. Retrofitting methods
3. Technology and solutions in practice
4. Implementation and performance

3.4.1.1 Respondent and project characteristics

Of the given categories, the majority of respondents represented architects (23), civil/structural engineers (20) and BER assessors / energy consultants (17). Table 3.3 indicates the number of respondents involved from each category of participating stakeholders.

<table>
<thead>
<tr>
<th>Professionals</th>
<th>Respondents (n=90)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Architect</td>
<td>23</td>
</tr>
<tr>
<td>Civil engineer/Structural engineer</td>
<td>20</td>
</tr>
<tr>
<td>BER Assessor/ Energy consultant</td>
<td>17</td>
</tr>
<tr>
<td>Construction manager</td>
<td>7</td>
</tr>
<tr>
<td>Building surveyor/ engineer</td>
<td>7</td>
</tr>
<tr>
<td>Quantity surveyor/ cost consultant</td>
<td>5</td>
</tr>
<tr>
<td>Contractor</td>
<td>3</td>
</tr>
<tr>
<td>Energy engineer/ manager</td>
<td>2</td>
</tr>
<tr>
<td>Researcher</td>
<td>2</td>
</tr>
<tr>
<td>Other</td>
<td>4</td>
</tr>
</tbody>
</table>

Respondents’ retrofit experience was recorded in terms of range of frequencies as shown in Figure 3.2. These results indicate that semi-detached and detached buildings represent the most common types of building retrofits. Approximately 27% (n=17) and 22% (n=15) of professionals have worked on more than 16 projects involving semi-detached and detached dwellings, respectively. Comparatively, a trend was observed towards a low rate of retrofitting of non-domestic buildings in Ireland.
Chapter 3. Attitudes and approaches of construction professionals in Irish retrofit industry towards achieving nearly-zero energy buildings

The purpose of building retrofits drives the performance requirements in a retrofit, approximately 82% of respondents highlighted energy and cost savings, whereas 69% identified renovation (Figure 3.3). This makes it clear that renovation and energy efficient refurbishment are carried out in parallel by most businesses, as illustrated in Figure 3.3. On the other hand, about 26% of respondents reported that the typical purpose was to improve indoor air quality and lighting. Also, only 29% of respondents noted ‘code compliance’ as a purpose of their retrofit in their projects.

Figure 3.2 Types of retrofit projects

Figure 3.3 Typical purposes of retrofit projects
Chapter 3. Attitudes and approaches of construction professionals in Irish retrofit industry towards achieving nearly-zero energy buildings

3.4.1.2 Retrofitting methods

To enable a successful retrofit upgrade project, integration of multiple actors is crucial [43], encompassing the perspectives of the professionals involved and the careful choice of retrofit strategies, audit procedures, and regulations. Varied results were observed when appraising the factors governing the choice of retrofit strategies. For example, Figure 3.4 demonstrates that 51% of respondents considered ‘proven solutions and technologies’ as the major factor, as they aimed to minimise risks of new systems. Overall, 90% recorded that ‘cost involved’ is the driving factor for their choices in retrofit planning. This is supported by the fact that the market is currently in the process of developing cost-effective retrofit upgrade options and financing schemes for building owners. High upfront costs and homeowners’ reluctance for long-term cost savings over short-term expenditures are key barriers in Ireland [44]. Factors such as decision-making frequency, awareness and engagement, budget limits and willingness to pay affect the energy retrofit uptake.

![Figure 3.4 Factors governing choice of retrofit strategies](image)

The survey also gauged some of the most frequently used audit practices before and after the building retrofits. Audit practices define state-of-art being used in practices. The responses, as shown in Figure 3.5, highlight that 80% of respondents recorded visual inspection as their standard practice. Yet this method is not effective in diagnosing all the problems in buildings to be retrofitted. On the other hand, only 30% of respondents selected on air-tightness test as an audit procedure. The air-tightness test generally involves a blower door test that determines the air-infiltration rate into the building and is a standard practice in Ireland [45]. This is also included as an option for calculating background air leakage in and out of a dwelling in the Dwelling Energy Assessment Procedure (DEAP) methodology required for the award of a BER. Infrared imaging is used to detect the thermal bridging, heat losses, and air-leakages.
Chapter 3. Attitudes and approaches of construction professionals in Irish retrofit industry towards achieving nearly-zero energy buildings

However, only 22% of construction professionals reported it use in their projects. This test is not commonly used as the equipment is costly compared to the air-tightness test.

To understand the extent of their involvement, the level of engagement of stakeholders was assessed in domestic and non-domestic retrofit projects. Respondents selected the categories they had involved in their projects. Figure 3.6 demonstrates a lack of participation of financing agencies, housing associations, local authorities, NGOs and technology manufacturers. These stakeholders are important for overall market development and adoption of retrofits by owners [46].

Figure 3.5 Audit methods used in practice

Figure 3.6 Stakeholders involved in domestic and non-domestic projects
Chapter 3. Attitudes and approaches of construction professionals in Irish retrofit industry towards achieving nearly-zero energy buildings

Use of regulations and building standards drives effective implementation of maximum thermal conductivity (defined by U-values) for opaque and non-opaque elements, air-tightness levels, fire norms and other building parameters. The observed trends in standards and regulations compliance were surprising (see Figure 3.7). 20.9% of respondents do not follow any standards in non-domestic projects, whereas about 6.6% of respondents work without any standards in domestic retrofits. BER and general building regulations are common due to effective and mandatory policy enforcement by the Irish government.

![Figure 3.7 Building regulations followed in practice](image)

3.4.1.3 Technology and solutions in practice

The availability of efficient construction methods, material, technologies and modelling tools and their use in retrofit industry in Ireland require greater acceptability to ensure the achievement of the nZEB goals. A section of the survey focussed on assessing the applicability of efficient methods and their implementation by retrofit industry actors.

Firstly, the construction professionals were asked to rate the requirement of retrofit analysis and modelling tools, across six categories, in order of their importance (Figure 3.8). A diverse response to these analysis methods indicates a low appetite and/or technical skill sets for computer modelling by construction professionals in the Irish retrofit industry. On the other hand, project planning tools were rated well above other tools. Different opinions were expected here as a broad range of construction professionals completed the survey and so their needs, experience and training vary significantly. However, there seems to be a requirement or an opportunity to inform construction professionals of the potential value of these tools at different stages of retrofit upgrade projects.
Furthermore, there has been a diverse trend observed in the type of facades retrofitted. 80% of respondents retrofitted façades with masonry cavity walls, approximately 66% selected single leaf masonry and 64% selected concrete block masonry. Highly glazed facades received the least attention (approximately 11%). Figure 3.9 indicates that a low percentage of the survey sample have experience with retrofitting of glazed facades.

One of the aims of this survey was to ascertain the deficiency in the availability of appropriate solutions for retrofit upgrades to buildings. Figure 3.10 shows a total of 39% respondents expressing a lack of solutions to deal with cold bridging. Thermal breaks are very challenging when dealing with retrofits [47]. Thermal insulation is the most widely available material, yet 23% of professionals reported a lack of availability and suitable insulation for their projects. This is potentially due to regional barriers in Ireland, such as transport, manufacturing, and imports. Acoustic insulation, building energy management systems and hot-water systems were among others that were of concern to 21% of respondents.
In response to an open-ended question, the professionals shared their views on the cost-effectiveness of the retrofit technologies and systems.

- ‘The product I felt was least effective was a geothermal heat pump, as the energy used to run the pump outweighed the benefit’
- ‘Solar hot water was cost-ineffective’

Overall, they experienced that Mechanical Ventilation and Heat Recovery (MVHR) systems, heat pumps, geothermal heat pumps, solar PV and hot water systems may not generate enough payback through savings. Some studies show that few of these systems have higher investment cost, therefore, they are not cost optimal solutions for retrofits [48], [49]. On the other hand cost analysis of a retrofitted house in Ireland by Mc Guinness [50] with MHVR, heat pump, solar PV, hot water panel was found to be cost optimal with the primary energy demand of 84 kWh/m²/yr [51]. Automated window opening systems and their high maintenance costs were also not cost-effective according to one respondent. Due to difficulty in scheduling works with residents, some respondents noted that cavity wall pumped insulation proved cost ineffective. Zone radiant heated slab tile flooring was among others that did not perform as expected after the retrofit.

### 3.4.1.4 Implementation and performance

The survey also assessed implementation and performance of projects, both pre- and post-retrofit, in terms of BER ratings. As shown in Figure 3.11, the majority of buildings had poor pre-retrofit primary energy performance and ranged from C3 (>200-225 kWh/m²/yr) to G (>450 kWh/m²/yr).
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kW/m²/yr). The highest number of responses were recorded for detached, semi-detached, end-terrace and mid-terrace houses. Recording the post-retrofit performance, Figure 3.11 also demonstrates the BER that professionals were typically able to achieve in their projects. The largest response rates were recorded for the B1 (>75-100 kW/m²/yr) rating, followed by C1 (>150-175 kW/m²/yr) and B2. Current practices are facing multiple challenges in retrofitting existing dwellings to very high performance, i.e. the band of A1 (≤25-25 kW/m²/yr) to A3 (>50-75 kW/m²/yr) which applies to nZEB for new buildings.

![Figure 3.11 Pre- and post-retrofit performance BER](image)

Informed decision-making and awareness among occupants, users and owners is essential to increase the knowledge level and propagate the benefits of retrofits [52]. It also becomes imperative to give recommendations for maintenance and repairs. The professionals rated each level of consultation frequency - shown in Figure 3.12. 45% of respondents recorded that they generally consult the owners frequently for decision-making, while 48% reported that they sometimes consulted users. It is a concern that 13% and 12% of respondents never consulted with occupants and users, respectively, while only 9% and 2% always consulted occupants and users. This is an important finding as Moran et. al [53] highlighted the importance of understanding occupant behaviour to determine appropriate solutions to reduce energy
consumption and/or improve thermal comfort in buildings. Retrofits can motivate higher retrofit uptakes if owners, occupants and users are consulted regularly during the process [54].

Figure 3.12: Frequency of consultation

The survey also highlighted issues and difficulty levels encountered during retrofits. From Figure 3.13, it is evident that the majority of the stakeholders expressed problems with the costs, skilled labour and quality, installation and performance level of components. However, most respondents stated these levels to be average for the adaptive technology, component size, aesthetics, flexibility in use, installation and operation and performance level.

Figure 3.13: Issues in retrofitting of buildings

General findings
The nZEB benchmark requires deep intervention into current industry practices and scoping out of regular problems, such as lack of information about ways to improve energy efficiency, evaluation of energy performance post-retrofits and continuous end-user feedback. The attitudes of industry stakeholders are key in shaping retrofits over the coming decades. The retrofit upgrade market of buildings in Ireland has too many conflicting opinions for achieving
the nZEB goals as understood from these results. Value and effectiveness of retrofits is generally not documented sufficiently frequently and, therefore, it becomes very difficult to access such information. A thematic analysis was conducted on the survey results as it offers deep descriptions on the data and generate unexpected insights [55]. Since there were four predetermined themes, it provided a framework to analyse the data and extract the findings in three major categories (market trends, advanced measures, government and public measures).

**Market trends**
The results of the survey indicate that residential retrofits are favoured by the market in terms of schemes, technology and products available. The market has yet to make many strides in retrofitting non-domestic buildings, which face bigger challenges and offer larger energy saving opportunities. Results suggest a lack of information on energy-saving technologies and the lack of availability of many retrofit technologies. For example, approximately 20% of respondents reported that basic components like windows and hot-water systems are difficult to source. It was further concluded that there is major dissatisfaction among professionals towards the supply of specific products. Generally, professionals have built up trust with existing suppliers and may avoid experimenting with new manufacturers and their products. This could explain the challenges in achieving low-energy targets as seen in BER results. About 90% of the professionals highlighted cost as the major barrier in decision-making and product selection. Grant support is currently limited and requires a new or reformed model to accelerate retrofit uptake by owners. The hesitation to overspend on retrofitting costs and unreliable paybacks is also a barrier. Lack of skilled workers is a major concern, as raised by 40% of the respondents. Up-skilling programs by the government have yet to be fully unveiled, but are gradually being introduced over the coming years. For example, the BUILD UP Skills training programme for craftsmen and on-site workers was concluded in 2013 [56]. As a follow-up, QualiBuild project based on the BUSI recommendations was introduced for training of construction workers and is set for national roll out in 2016 [57].

**Using advanced measures**
The results also suggest a deficiency in the use of new analysis and modelling tools within the retrofit industry. Many professionals have not embraced new measurement and verification methods, and there was a deficiency of some audit practices. This may expose issues within the industry, such as inexperienced auditing. Improper implementation of audit practices can lead to the lowering of opportunities for improving the energy efficiency of buildings. The
recommendations required for building envelope, attic insulation, air-tightness, thermal breaks and condensation are often difficult for owners to understand. Therefore, professionals must follow systematic procedures for auditing.

**Government and public measures**

Many professionals cited the role of government as a major factor affecting their practices. They pointed towards loopholes in policies, funding support and the approach to retrofitting. Also, there is a dearth of data available for the evaluation of the impact of retrofit upgrades, which could inform policies and funding mechanisms. One potential solution identified in the survey results is for greater post-retrofit consultation with owners and occupiers, including the collection of data on energy performance. In general, the survey results highlighted a number of areas concerning legislation and policy and a workshop was organised to confirm the validity of survey results and to unpack the attitudes and approaches of retrofit industry stakeholders in greater depth.

3.4.2 Workshop results: Engaging retrofit stakeholders

A detailed all stakeholder engagement activity were organised in the form of an nZEB-retrofit workshop in August 2015, following the surveys which were only for nZEB experts and actors. This attracted 85 participants from across Ireland. The objective of the workshop was to bring together a wide range of stakeholders to share expert opinions on meeting clients’ needs for building retrofits, as well as the nearly zero-energy targets set by the European Union. They comprised architects, academics, planning authorities, community partners, contractors, construction and facility managers, engineers, financiers, manufacturers, consultants, BER assessors, housing associations, general clients, property owners and researchers, among others.

While the survey results indicated industry specific concerns and current issues, the workshop focussed on discussing various other elements of the growing retrofit market by assessing policy and regulation level, comfort, state-of-art and their impact. Hence, the workshop was organised into four plenary sessions with stakeholders from several organisations presenting their work under the following themes:

i. Governance, standardisation, and economics

ii. Health, comfort, indoor air quality, and energy performance

iii. Impact through technology, innovation, and implementation
iv. Showcasing energy efficient retrofits

Each of the plenary sessions was initiated by contextual presentations followed by moderated discussions which helped to gain insight into the different perspectives of the stakeholders and to identify points requiring further attention. The speakers presented their work and informed the stakeholders about cause and effect relationships between the problems and solutions that would allow effective retrofitting of the building stock in Ireland. One of the major objectives was to identify the role of government in the retrofit processes and their level of ambition, policies, finance, energy efficiency obligation schemes and skill gaps. Opportunities to address health and human comfort, the status of the innovation scenario in the market and best practices were also discussed. A summary of the key discussions is presented in Table 3.4 leading to an assessment of the stakeholder requirements, perspectives on policies, market conditions and expectations of the Irish market.

Table 3.4 Summary of workshop discussions

<table>
<thead>
<tr>
<th>Categories</th>
<th>Key issues and initiatives discussed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building envelopes/façades</td>
<td>Retaining character requires attention in regulations&lt;br&gt;Envelopes must be designed with consideration given to the vicinity&lt;br&gt;Form of the building is not usually taken into consideration in retrofits&lt;br&gt;Roof height clearance is required from authorities during retrofits</td>
</tr>
<tr>
<td>Community initiatives</td>
<td>Community wind farms have been proposed&lt;br&gt;Web and television programmes should reach out to the community about retrofits</td>
</tr>
<tr>
<td>Cost optimality</td>
<td>Retrofits must be carried out with renovation to save up to 50-60% cost&lt;br&gt;Holistic approaches that consider Life Cycle Cost (LCC) are required&lt;br&gt;Larger problems and failures are encountered in most cases of cost-optimal retrofits&lt;br&gt;Economic value of house is related to BER, it should be based on LCC</td>
</tr>
<tr>
<td>Financial structure</td>
<td>Financing institutions must support retrofits (e.g. banks, insurers etc.)&lt;br&gt;Specific financing schemes are required to increase the uptake of retrofits&lt;br&gt;Bigger incentives are required for achieving higher BER</td>
</tr>
<tr>
<td>Government initiatives</td>
<td>Government should introduce plans to help pay for micro-generation&lt;br&gt;On-site energy storage initiatives should be undertaken&lt;br&gt;SEAI should document EPDs, embodied energy and embodied carbon for products in Ireland&lt;br&gt;Funding systems require better structure for effective distribution&lt;br&gt;Tax rebates should be given to professionals for effective services</td>
</tr>
<tr>
<td>Industry initiatives</td>
<td>A Home Quality Rating project should address embodied energy&lt;br&gt;One-stop shops are required to defragment the industry</td>
</tr>
<tr>
<td>Information gap</td>
<td>Public is not informed about heat energy savings&lt;br&gt;Users should be informed about the availability of credible retrofitters in the vicinity&lt;br&gt;Technical information is required for public to understand the needs of professionals&lt;br&gt;Technology suppliers have limited information about products&lt;br&gt;There are under-qualified professionals in the industry</td>
</tr>
</tbody>
</table>
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<table>
<thead>
<tr>
<th>Manufacturers and suppliers</th>
<th>Difficult to get unbiased test information about the product</th>
</tr>
</thead>
<tbody>
<tr>
<td>nZEB performance target</td>
<td>Impracticality in payback of renewables by 2020</td>
</tr>
<tr>
<td>Performance monitoring</td>
<td>Calibration of temperature sensors requires huge effort</td>
</tr>
<tr>
<td></td>
<td>Energy consumption data in kWh/m$^2$ does not reflect the size of the household</td>
</tr>
<tr>
<td></td>
<td>Lack of protocols for data collection and verification</td>
</tr>
<tr>
<td></td>
<td>Big gap in performance and predicted/ design performance</td>
</tr>
<tr>
<td>Professionals</td>
<td>People are not ready to pay high fees for professional services</td>
</tr>
<tr>
<td></td>
<td>Professionals are ill-equipped with latest advances in retrofitting and support tools</td>
</tr>
<tr>
<td>Radon concentration</td>
<td>Ventilation and passive sump are promising measures</td>
</tr>
<tr>
<td></td>
<td>Positive pressurisation of dwelling is effective to prevent radon concentration</td>
</tr>
<tr>
<td></td>
<td>Few people are aware of radon concentration and its health effects</td>
</tr>
<tr>
<td>Regulation standards</td>
<td>Flaw in DEAP regarding glazing calculations</td>
</tr>
<tr>
<td></td>
<td>SR-54 for retrofits has very basic view for professionals and the public</td>
</tr>
<tr>
<td></td>
<td>General guidelines for nZEB are required</td>
</tr>
<tr>
<td>Retrofits</td>
<td>Opportunity to improve built environment</td>
</tr>
<tr>
<td></td>
<td>Operational energy requires integration in retrofit planning</td>
</tr>
<tr>
<td></td>
<td>Embodied energy needs elaboration in regulations and industry</td>
</tr>
<tr>
<td></td>
<td>End user requirement needs more detail</td>
</tr>
<tr>
<td>Supply and demand</td>
<td>Problems convincing people of connection between supply and efficiency</td>
</tr>
<tr>
<td></td>
<td>Customer wants cheapest solutions</td>
</tr>
</tbody>
</table>

During the workshop, varying agreement levels were observed in the discussions of the topics listed in Table 3.5. There was consensus reached on several items agreed to be of immediate concern whereas there was no consensus on topics such as Life cycle costing, embodied energy and risk assessments among others. However, there were mixed responses to issues such as holistic retrofits and recycling or reuse. The study measured the depth of barriers and challenges towards retrofitting that exist among the industry stakeholders’, users, clients and authorities and these are discussed in Section 3.5. Common concerns highlighted issues such as the level of clarity in standards, which are required to be more specific and focused. Interest was also expressed in the initiation of awareness programmes.

### Table 3.5 Summary of topics discussed and their consensus levels

<table>
<thead>
<tr>
<th>Consensus</th>
<th>No consensus</th>
<th>Neutral</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy monitoring methods</td>
<td>Life cycle costing</td>
<td>Ambition setting process</td>
</tr>
<tr>
<td>Effective supply and demand</td>
<td>Embodied energy</td>
<td>Measurement systems and methods</td>
</tr>
<tr>
<td>Public awareness and engagement</td>
<td>Risk assessments</td>
<td>Improved built environment</td>
</tr>
<tr>
<td>Stimulation of financiers</td>
<td>Environmental factors</td>
<td>Holistic retrofits</td>
</tr>
<tr>
<td>Educating craftsmen</td>
<td>nZEB targets</td>
<td>Courses and training</td>
</tr>
<tr>
<td>Data from public</td>
<td>Comparative information on products</td>
<td>Recycling and reuse</td>
</tr>
<tr>
<td>Market transformation</td>
<td>Tax rebates to professionals</td>
<td>District water heating</td>
</tr>
<tr>
<td>Cost optimisation</td>
<td></td>
<td>Non-domestic buildings</td>
</tr>
<tr>
<td>Building character</td>
<td></td>
<td>(commercial etc.)</td>
</tr>
<tr>
<td>Technical, economic and behavioural data</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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The workshop helped in understanding diverse opinions within the retrofit industry, bridging the gap between stated-preference survey results and the motivations of industry professionals. One of the main findings was that the introduction of new regulations and their acceptance is not mutually understood among professionals due to an information gap. People trust established technologies, as newer technologies often do not declare accurate performance information. The value supply chain is weakened by skill gaps and the lack of one-stop-shops affects the uptake of available solutions by owners. Building envelope/façade retrofitting was identified as one of the key issues throughout the survey and workshop and, therefore, in-depth interviews were planned to elaborate on their role and importance in retrofits. Since there is a multitude of issues available for in-depth interviews but one was prioritised over others.

3.4.3 Interview results: Investigating envelope/façade retrofits

In-depth interviews were conducted as the final component of this study on retrofit practices. The interviews were semi-structured of 60 minutes’ duration which gave the interviewees the freedom to share their thoughts, ideas and experiences. Interview questions focussed on the professionals’ most interesting and useful experiences and solutions in the area of building envelope retrofits that have maximum impact on building energy [58]. The results of the interviews are based on responses to open-ended questions which reflected the independent perspective of the interviewees. A thematic analysis was conducted to analyse the results.

A total of 11 interviews were conducted and participants were selected from different backgrounds and practices in renovation and refurbishment activities in domestic and non-domestic buildings following purposeful sampling technique. The aim of this phase of the study was to interview the process actors as widely as possible. The interviews were divided into predetermined four main themes of descriptive and normative questions: (1) Experience of envelope retrofits, (2) Assessment of design, construction and delivery, (3) Technology and systems, and (4) Issues and concerns over envelope retrofits. Further, the findings were collated in each theme to present the overall picture. Quotations have been used to improve the interpretation of the findings.

3.4.3.1 Experience of envelope/façade retrofits

There appears to be a lack of motivation for the deep retrofit of building envelopes, mainly due to cost-driven factors. Generally, residual building life is shorter to complete longer paybacks for envelope retrofits with larger upfront investment [59]. Better ventilation concepts
are required for dwellings, together with maximising the use of solar gain and natural light. There should be minimum environmental impact of the envelope retrofit during its life cycle.

*It is a cost dependent component and has a lot to do with affordability...I think Passive House Standard is going to be the norm...people are buying the level of comfort*

60% of participants considered envelope retrofits to be a fundamental problem.

*There is extreme ignorance in Ireland towards envelopes...preservation of original architecture is important...*

Contractual documents are generally poor and there is lack of integrated design practice and consensus over standardised detailing. There are challenges with the inclusion of services, their connections in the envelope, workmanship, moisture penetration, noise from mechanical ventilation system, and operational energy costs.

*I had contractual issues in the projects and there is no integration of work in the projects...*

General methods of diagnosis involved in projects are visual inspection, BER assessments, occupant feedback and sequential evaluation, air-tightness and hygrothermal analyses. Preference is given to the over-riding issues which are budget dependent and driven by client requirements. Interviewees expressed that there are considerable risks in eliminating thermal bridges and this requires additional work. External insulation, tapes and membranes are being used as mitigating measures in retrofit projects, as well as thermal imaging and careful design of projected features.

*It is difficult to get rid of them all...issues with semi-detached owners...occupancy of the building is a serious problem while retrofitting...*

### 3.4.3.2 Assessment of design, construction and delivery

5 out of 11 interviewees outlined that clients are typically more concerned with image update than energy in retrofits.

*It matters a lot to the clients...clients are ready to pay for the aesthetics in the projects...*

Types of construction materials, preservation, insulation condition, the status of the building, budget and client needs are some of the main factors to be considered in envelope/façade retrofits. 30% of interviewees recorded that no assessments are carried out post-retrofits. Half of the interviewees use BER, meters/sensors with data logging, feedback from occupants and calculations as measures to record post-retrofit performance.

*They are satisfied generally and have a comfort takeback...sometimes get feedback from the residents...*
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They described that current regulations do not allow significant changes in geometry of the existing building envelope when considered together with cost and space considerations. The addition of windows, glass replacement, re-roofing applications and south-side extensions were the most common envelope improvement in their projects. A few professionals indicated that there is large and sensible growth in the market. Residential solutions are easily available compared to non-residential. Furthermore, suppliers do not focus on specifications during retrofits.

*I found residential solutions good and well performing...specification understanding is not good...*

The general expertise of the interviewees was in traditional masonry, timber frame, stone cladding, concrete block masonry, mass concrete and curtain walling. Professionals have uncertainty over performance and affordability of advanced materials and there is little motivation for experimentation in their projects. 50% of the interviewees consider embodied energy to be important, but found embodied energy considerations unfeasible for small-scale retrofits with low-budgets.

*Yes, it is important but generally in practice it is not taken into account...it is important information if provided correctly by manufacturer...*

They also do not find Part-L of the building regulations [18] sufficiently detailed and comprehensive for practice. To adhere to regulations, interviewees generally follow Passive House Standard, EnerPHit, NSAI, LEED and BREEAM. As a measure for passive design, they have used eco-cements, GGBS, wood based insulation, extensions to south faces, double walls, passive slabs and roof transformation.

### 3.4.3.3 Technology and systems

Among the expectations for new technologies were ventilation systems integrated with façades, breathable insulation for timber facades as well as thermodynamic insulations, waste heat recovery solutions, effective CHP technology and smaller heat pumps. The anticipated risks in envelope retrofits were internal humidity levels, interstitial condensation and moisture accumulation, the life of the insulation and overheating. 80% of the interviewees were conscious of reducing energy consumption of the buildings in their retrofit projects and achieving minimum standards is the general target.

*It is absolutely essential to have this approach in the current scenario... We place effort to achieve good performance...*
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Regarding the preference between cost and energy performance, longer paybacks of new efficient systems deter their adoption and achieving a balance between the two is the target, although clients play a decisive role. The tools used for design and analyses included software such as WUFI, SCI-Therm, Sketchup, Builddesk, DEAP and PHPP, as well as the use of rules-of-thumb and calculations in MS Excel.

3.4.3.4 Issues and concerns over envelope retrofits

Among other concerns, off-site training for envelope retrofits was highlighted by 3 interviewees and they regarded licensing of practitioners in retrofits as important. There should be insurance schemes to pay for the damage caused during deep retrofitting of building envelopes. Norms and construction details in retrofits should be established to enable the industry to become aware of its importance such as newly introduced SR 54:2014 [20].

SR 54 which was recently finally released this month is a very limited piece of work (some of its guidance is high risk) but no doubt... any messages that conflict with it will be regarded as retrograde or non-compliant...

Clear guidance on the suitability of materials over their life cycle should be provided in the regulations. Improved methods and guidance on ventilation control are also required for better retrofits.

These interview results suggest that the construction sector is fragmented and that there lacks coherent strategies surrounding retrofit processes. The interviews provided a detailed representation of the individuals’ activities where the barriers are generally financial, technical, governmental, social and organisational. The practicing professionals have varying opinions over the acceptable quality levels of nZEB practices and, therefore, limited efforts to achieve nZEB levels were seen. The lack of skilled workers, contractual issues, product quality, ready available appropriate technology, lack of knowledge and motivation can be observed in the current practice of professionals. There are challenges to the envelope retrofits for maintaining cultural and historic values. There are high performance ambitions from the existing buildings, but existing solutions do not support the efforts. The key to the organisation of retrofit efforts requires commitment, cooperation and collaboration by the nZEB actors.

3.5 Summary and conclusions

The three-tier study outlined the spectrum of attitudes and approaches in the retrofit industry, highlighting multiple barriers, gaps, and challenges in Ireland. The results from section 3.4 are
summarised in Table 3.6 below under two broad headings: (a) Practice and Industry (Technical, Environmental, and Industrial), and (b) Enforcement and Governance (Legislative, Social, and Economic); and followed by comprehensive briefings on these categories.

Table 3.6 Barriers, gaps and challenges in the retrofit industry in Ireland

<table>
<thead>
<tr>
<th>Practice and Industry</th>
<th>Enforcement and Governance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technical</td>
<td>Legislative</td>
</tr>
<tr>
<td>• Low quality auditing</td>
<td>• Lack of incentives</td>
</tr>
<tr>
<td>• Lack of openness to new solutions</td>
<td>• Poor ventilation standards</td>
</tr>
<tr>
<td>• Absence of coherent technologies</td>
<td>• No documentation on embodied energy for retrofits</td>
</tr>
<tr>
<td>• Lack of standards and details</td>
<td>• Inflexibility in building regulations w.r.t. retrofits</td>
</tr>
<tr>
<td>• Low cost development of technologies</td>
<td>• Less focus on operational energy in standards</td>
</tr>
<tr>
<td>• High reliability of proven solutions</td>
<td>• Lack of general reference manuals, and comprehensive nZEB regulations</td>
</tr>
<tr>
<td>• Variation in measured and actual performance</td>
<td>• DEAP does not address all issues</td>
</tr>
<tr>
<td>Environmental</td>
<td>Social</td>
</tr>
<tr>
<td>• Low preference for IAQ and acoustics</td>
<td>• Lack of awareness of long-term retrofit benefits</td>
</tr>
<tr>
<td>• Neglecting air-quality testing post retrofits and radon concentration</td>
<td>• Lack of involvement of owners/occupiers</td>
</tr>
<tr>
<td>• Limited availability of recyclable products</td>
<td>• Missing communication to owners</td>
</tr>
<tr>
<td>• Little emphasis on LCA and its impact</td>
<td>•Insensitive towards architectural and cultural aspects</td>
</tr>
<tr>
<td>• Few studies on health impact of retrofits</td>
<td>• Insufficient infrastructure for growing population</td>
</tr>
<tr>
<td>• Passive design methods rare in practice</td>
<td>• Community-based energy production methods not adopted</td>
</tr>
<tr>
<td>• Environmental approach less feasible in small scale retrofits</td>
<td>• No desire or support from client to record data and monitor</td>
</tr>
<tr>
<td>Industrial</td>
<td>Economic</td>
</tr>
<tr>
<td>• Less involvement of experts</td>
<td>• High upfront costs for owners</td>
</tr>
<tr>
<td>• Unskilled operators in market</td>
<td>• Tax-free opportunities should be explored</td>
</tr>
<tr>
<td>• Lack of availability of one-stop solutions</td>
<td>• Measure for non-domestic buildings required</td>
</tr>
<tr>
<td>• Low collaborative approach in projects</td>
<td>• Envelopes considered as cost-driven components</td>
</tr>
<tr>
<td>• Conflicting opinions among stakeholders</td>
<td>• Imbalance between typology of building retrofit vs split incentives between owner and industry</td>
</tr>
<tr>
<td>• Requirement of assessment of chain effects in retrofits</td>
<td>• Lack of retrofit services in rural areas with focus only on urban areas with high economic gains</td>
</tr>
<tr>
<td>• Lack of comparative product information</td>
<td></td>
</tr>
</tbody>
</table>

(a) Practice and Industry
One of the key technical barriers observed in practice are low quality auditing and low versatility for intervention in existing buildings. Professionals lack expertise on non-domestic retrofits, on the other hand there is a general trend of reliance on existing solutions and a lack
of adoption of new solutions for domestic retrofits. In general, suppliers have inadequate technical information with a prevalent absence of coherent technologies that can work with existing systems. Very few retrofit concepts are available in practice to deal with solar gain, natural light issues and hygrothermal evaluation. An uneven mix of retrofit experts exists in the industry and retrofit businesses lack technical standards for nZEB. This suggests a greater need for identification of dedicated technical roles and responsibilities and standardised detailing for retrofits within the practices. There are many technical challenges, such as the upgrading of protocols for retrofitting, low-cost development of retrofit technologies, and a lack of proven solutions and expertise. Correct information on products and monitoring actual energy performance in retrofits are seen as important factors to overcome.

It is also worthwhile to note that a much lower preference was observed for environmental concerns than for technical challenges in retrofit practices. Barriers such as improvement in IAQ and acoustics are generally left unaddressed in projects with the emphasis lying only on energy savings. Professionals often don’t conduct radon concentration or air-quality testing inside the building post-retrofits. With a lack of focus on environmental retrofit approaches in small-scale retrofits and limited availability of recyclable and re-usable products in the market, there is insufficient emphasis on Life Cycle Assessments (LCA). Furthermore, few studies exist which quantify the health issues of pre/post retrofits in Ireland. These challenges require fast retrofitting solutions and the exploration of local materials for manufacturing environmentally-friendly building products. Also, many more studies are required to examine the environmental impact of building envelopes. Retrofit practices must overcome the challenges encountered in previous retrofits such as noise pollution, health effects on workers and recoding of radon concentration. This can be achieved by integrating these challenges within policy frameworks and national implementation strategies for environmental improvement.

To improve retrofitting in Ireland, industry is a crucial sector in dealing with technical, environmental and other barriers. There is a low level of involvement by experts in domestic retrofits, while contractors are carrying out retrofits at very low rates. On the other hand, unskilled operators are selling products with little understanding of specifications. The lack of sharing of information and knowledge among stakeholders gives rise to conflicting opinions among the stakeholders. There is a huge gap between the development of models for contractual arrangement in retrofits and the parallel assessment of the chain effects in buildings being retrofitted. A government guide to contractual structures for retrofit businesses can be
very useful to address this issue. Holistic retrofit methods and greater collaborations are required in the industry and among different actors for the improvement of future retrofits.

(b) Enforcement and Governance
An absence of government incentives for achieving higher energy efficiency goals was described in this study. Lack of flexibility in building regulations for retrofits (e.g. extensions, change in geometry etc.) and traditional measures for improvement of existing facades were some of the major barriers observed. There is an absence of comprehensive documentation and databases to address environmental impacts of products in Ireland. Furthermore, greater control of low-quality retrofits taking place across the country and compilation of explanatory nZEB regulations based on consensus are key challenges to be pursued through legislation and policy interventions.

There are many social barriers in retrofit projects arising mostly from the client side. Generally, there is less desire and support from the client/owner to record and monitor data on energy performance and retrofit decisions are made by the client/owner with little or no experience. Professional advice is not sought in the majority of retrofit projects and several architectural and cultural issues limit the possibility of retrofits. Community-based initiatives are missing in practice and information on credible retrofitting professionals and contractors in the regions are not available. A lack of infrastructure and insensitivity towards harmonising existing building with surroundings are questions of deep concern. The opportunities to explore local energy producing methods, and technologies and concepts to improve the quality of built environment are also important gaps to be addressed. However, it may also be noted that achieving higher energy performance with historical buildings or protected structure is comparatively difficult. Another of the major challenges is the communication of benefits about the monitoring of data to the residents and the role of professionals in retrofits. Increasing the retrofitting rate to match the demand and availability of unbiased information from the manufacturers are some of the other challenges to be met.

Society is closely affected by the economic barriers in retrofitting whereas greater inclination is found towards residential sector retrofits due to reliable sources of income. Higher density of retrofit businesses exist in urban areas with higher economic gains. As can be noted above through the practice and industry trends, client orientation is generally towards buying cheaper solutions with lower budgets - high upfront costs make them reluctant to uptake retrofits. One
of the important barriers affecting their motivation for retrofits is short-term ownerships affecting long-term paybacks and initial investment into a property, and the Governments’ lack of funding for ancillary works with null tax rebates for professionals providing retrofit services. A rising trend in Ireland suggests that property values are affected by BER, but not by life cycle potential which presents a major social barrier. These economic gaps demand motivational measures for retrofitting non-residential buildings as they consume a significant amount of energy. Solutions for retrofitting while maintaining occupancy and exploring tax-free opportunities for building retrofit products can bring massive changes in the industry. Deep retrofit benefits must be elaborated for tapping into the existing opportunities in the Irish context through building regulations and policies. Significant challenges involve balancing the typologies for building retrofit and split incentives for uptake of such projects among the owners and industry. The spread of retrofit services across suburban and rural regions can make a huge impact in saving energy. This also includes calculating the economics of the retrofit for the owners without public funds, provision of incentives for achieving higher energy efficiency goals, and control on the escalation of the property values. Low-cost development of envelope retrofit components and lack of general agreement on retrofit strategies are other important concerns for retrofits.

**Concluding Remarks**

Individual stakeholders hold specific requirements which represent the industry as a whole. Many barriers can be overcome within the industry and its stakeholders, for successful growth of nearly zero-energy buildings (nZEB’s). The gaps that exist present an opportunity for adopting appropriate solutions for effective retrofitting. Technical lag among expert actors poses serious impacts on quality and performance of retrofits in Ireland and innovative measures for incentives. Tax benefits are required to further support the growth of retrofits. Environmental barriers are an integrated part of the industry and can be controlled through legislation. The legislative perspective has a deep influence over the motivation and approach of the professionals to follow nZEB targets. Also, social barriers can be eliminated by involving the occupants and owners and filling the necessary information gap along with ways to economise retrofitting. Several findings from this research can inform formulation of policy and practice standards that fall within the scope of environmental, economic and social regulations. The recognised gaps can be addressed by research and industry innovation through collaborative approaches and the support of the public. The overall collective picture represents
the attitudes and approaches of the industry stakeholders that define the shape and growth of the industry for future nZEBs.

### 3.6 Limitations of the study

This study represents a first step in understanding the major barriers in industry practices in Ireland. During this research there were several limitations, and which may have influenced the results and findings.

i. It is a convenience sample rather than a random sample and therefore this may affect the generalisability of the findings. This sampling technique may also include selection bias.

ii. The study focused on the construction industry Ireland, which experienced an unprecedented construction boom and collapse in the past 20 years. The Irish housing, construction, and retrofitting markets also include some significant differences from the remainder of Europe, e.g. high proportion of owner-occupiers and single-family dwellings.

iii. The study only considered construction professionals and did not include the perspectives of site workers and end users, this may have affected the scope of the findings.

iv. The survey questions were limited and generalised for a number of professionals, which restricted their flexibility to answer.

However, it is envisaged that the comprehensive three-tier methodology and varied sample enabled the capturing of a wide range of perspectives which we analysed in depth. It was clear that a number of key issues were raised at each stage by several participants. Therefore, further research is required to overcome these key issues in form of in-depth interviews for each category of stakeholders that could guide in developing successful retrofit initiatives for Ireland.
3.7 References


Chapter 3. Attitudes and approaches of construction professionals in Irish retrofit industry towards achieving nearly-zero energy buildings


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University of Southern California, 2013.


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Chapter 3. Attitudes and approaches of construction professionals in Irish retrofit industry towards achieving nearly-zero energy buildings


Chapter 3. Attitudes and approaches of construction professionals in Irish retrofit industry towards achieving nearly-zero energy buildings
Chapter 4: An Indoor Environmental Quality (IEQ) assessment of a partially retrofitted university building

4.1 Chapter overview

When retrofitting existing buildings, it is crucial to study the relationship of occupant satisfaction with thermal, visual and acoustic comfort and indoor air quality (IAQ). Based on the feedback from professionals in Chapter 3, the building retrofits are often of low-quality and ad-hoc (selective retrofit intervention without sufficient investigation of its impact) in implementation. Hence, this chapter presents a standards-based assessment of IEQ of a partially-retrofitted university building to evaluate the existing building performance and determine possibilities of further retrofit interventions.

The study combined methods outlined in EN15251 [14] and ASHRAE 55 [21] for the assessment. The university building consisted of 25 occupied zones. A data collection campaign was organised between June 2016 – May 2017 and involved audits, surveys and physical measurements (Appendix C). Indoor environment variables of indoor air temperature, humidity, mean-radiant temperature, air velocity, light levels, noise levels and CO₂ concentration were recorded in all the zones of the building. Point-in-time occupant surveys were conducted during the four Irish seasons in the offices to understand the occupant satisfaction levels. The templates for surveys were prepared based on CBE IEQ [63] survey and are given in Appendix D. The quantitative data from physical measurements were used to calculate occupants’ comfort (thermal, visual, acoustic) and IAQ. Also, the qualitative data collected from surveys were analysed and used to cross-evaluate the causes of discomfort. A major cause of problems with IEQ was the inefficient envelope that was only partially retrofitted and the absence of a mechanical ventilation system. In winter, the average indoor air temperatures were below the standard recommendations for existing building and the lecture rooms and post graduate rooms were observed to have poor indoor air quality in winter. In general, most of the occupants expressed satisfaction with lighting and noise levels.

This field-study is one of the first detailed studies to understand the relationship between IEQ and impact of ad-hoc retrofits in non-domestic buildings in temperate-oceanic climate. This study may also contribute to the development of retrofit standards specific to IEQ. In further chapters, this field-study is used for the identification of suitable retrofit measures for the case study building.
Chapter 4. An Indoor Environmental Quality (IEQ) assessment of a partially-retrofitted university building

This chapter has been published in the international journal ‘Building and Environment’ on July 2017. Sheikh Zuhaib conducted the field-study, carried out the tests, interpreted the data and wrote the manuscript. The article was co-authored with the primary supervisor Dr. Jamie Goggins who directed this research and commented on the manuscript at all stages. Dr. Richard Manton assisted with development of occupant surveys and field-study organisation. Dr. Corey Griffin advised on the design of measurement campaign. Dr. Magdalena Hajdukiewicz and Dr. Marcus Keane guided on the analysis of IEQ data.

Abstract

Achieving standards-based Indoor Environmental Quality (IEQ) in existing buildings is growing steadily due to the strong demand for deep retrofits in Europe. Existing non-domestic buildings pose challenges mainly due to occupancy patterns, lack of personal control over comfort and outdated building structures. Renovations of many post-war non-domestic buildings (>35 years old) have faced technical and financial challenges. Consequently, these buildings are often only partially retrofitted, which are often ad-hoc in nature. This paper describes the evaluation process of indoor environmental conditions in a partially-retrofitted university building in Galway (Ireland) originally built during the 1970s and partially retrofit in 2005. The research assesses criteria outlined in EN 15251 and draws on methods from ASHRAE 55 and CBE IEQ survey. Occupant surveys complemented by physical measurements were used to assess the compliance of IEQ parameters for thermal, visual and acoustic comfort and indoor air quality. The relationship between the performance of the building envelope and occupant comfort is described across retrofitted and non-retrofitted zones of the building. The results suggest that ad-hoc retrofitting of the façade did not make any significant difference to IEQ and occupants continued to adapt personally to the existing conditions. Their preferred satisfaction levels in the survey were lower than the measured thermal sensation. It is recommended that future retrofits are adequately planned and optimised to improve both IEQ and energy performance. A whole building retrofit approach must balance and include factors such as human health, building fabric and energy savings to avoid the pitfalls of current practice.

4.2 Introduction

A key factor in achieving healthy environments in buildings is the provision of a high level of Indoor Environmental Quality (IEQ) [1]. The awareness of impacts that are posed by poor
indoor environmental conditions has been studied across various research areas such as health and building sciences [2]–[4]. IEQ refers to the acceptable levels of thermal, visual and acoustic comfort in addition to Indoor Air Quality (IAQ) [5]. In both existing and new buildings, there is now an increased focus on the energy efficiency subsequent to the Energy Performance Buildings Directive (2010/31/EU) (EU, 2010). However, achieving energy efficiency does not automatically ensure better IEQ, particularly, in existing non-domestic buildings (built during post-war period). Building owners often do not consider improving IEQ as a means of keeping the running costs lower and rather invest only in immediate maintenance and operation. Energy efficiency has been a focus of different retrofit measures through shallow or deep retrofits [7]. So far, the cost-effectiveness of retrofits has not been adequately evaluated with respect to IEQ, thereby giving it low-priority compared to energy efficiency [8]. The lack of understanding of IEQ could have adverse effects on the occupants in the long run, such as health and respiratory problems [9]. The occurrence of health problems could directly affect the productivity of the occupants and induce higher costs on employers; therefore, quantification of productivity gains can directly motivate energy efficiency measures and lead to improvement in indoor environments of the buildings [10]. Furthermore, non-domestic buildings in Europe account for 25% of the total stock and have greater energy consumption per unit of floor area compared to dwellings [11].

Existing post-war (1945-85) non-domestic buildings such as offices, educational, commercial and institutional buildings have greater complexity than domestic buildings regarding internal environments: a larger number of occupants, a greater diversity of contaminants, mechanical systems for heating, ventilation and air conditioning (HVAC) and reduced personal control over thermal and ventilation conditions. Thus, maintaining satisfactory thermal comfort and IEQ conditions is one of the major challenges in existing buildings which are aimed to achieve nearly zero-energy building (nZEB) standards in the EU member states [12].

The REHVA position paper to the European Commission on the proposal to revise the EPBD [6] extensively promotes the application of methods to improve the indoor environment quality along with the energy efficiency [13]. The EN15251 standard [14] is a result of the EPBD and specifies the criteria for achieving better indoor environmental conditions. Other standards are under development such as ISO/TC-205 [15] and ISO 17772-1 [16] that aim to standardise retrofits.
Chapter 4. An Indoor Environmental Quality (IEQ) assessment of a partially-retrofitted university building

The primary aim of this study is: (i) to assess compliance with the criteria outlined in the standard EN15251 [14] (see Table 4.1) for the acceptance of IEQ in an existing university building (National University of Ireland Galway), and (ii) to assess the impact of ad-hoc, partial retrofitting of the building on the IEQ. To date, the application of these criteria is not clearly outlined in the standard for assessing compliance in terms of age of existing buildings and not significantly covered within scientific research for post-war non-domestic buildings. Approximately 37% of the non-domestic building stock (age between 31-50 yrs.) are likely to be retrofitted in the next 20 years as estimated in 2011 [17]. A steady increase of up to 3% of the annual stock of non-domestic buildings being retrofitted (light, medium and deep) was observed in countries like Netherlands, Belgium, Poland and Italy in 2013 [18]. Educational buildings account for the largest share of the oldest buildings in Europe out of which majority were constructed before 1980. Buildings from the post-war period are generally characterised by poor insulation, large single-glazed façades, larger floor plates, high costs for energy, and large carbon footprints.

<table>
<thead>
<tr>
<th>Category</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>High level of expectation and is recommended for spaces, occupied by vulnerable people with special requirements such as children, older people, those with reduced mobility etc.</td>
</tr>
<tr>
<td>II</td>
<td>Normal level of expectation and should be used for new buildings and renovations</td>
</tr>
<tr>
<td>III</td>
<td>An acceptable, moderate level of expectation and may be used for existing buildings</td>
</tr>
<tr>
<td>IV</td>
<td>Values outside the criteria for the above categories. This category should only be accepted for a limited part of the year.</td>
</tr>
</tbody>
</table>

4.3 Indoor Environmental Quality

The multi-annual European roadmap for energy efficient buildings describes IEQ as an important area of investigation by 2020 [19]. The environmental factors of thermal comfort, visual comfort, acoustic and IAQ define indoor environment quality [20]. Each of these will be discussed in the following subsections with respect to the latest standards and research.

4.3.1 Thermal comfort

Thermal comfort relates to the physical environmental factors in naturally ventilated and conditioned environments. It is expressed as “the condition of mind in which satisfaction is
Chapter 4. An Indoor Environmental Quality (IEQ) assessment of a partially-retrofitted university building

expressed with thermal environment” [21]. There is a strong correlation between energy consumption and international thermal comfort standards set for the buildings [22]. Air temperature, mean radiant temperature, air velocity and relative humidity are four physical environmental parameters that affect thermal comfort, whereas clothing value and metabolic rate are considered as personal parameters. A range of thermal comfort indices are available and derived based on Fanger’s equation of comfort such as Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) [21]. These indices are used in the assessment of existing buildings to determine the thermal comfort values over a long term. Thermal comfort is the most preferred factor for the evaluation of indoor comfort in comparison to visual, acoustic comfort and indoor air quality [23]. It was also found to have an impact on the perception of other IEQ factors [24]. Studies have indicated the failure of modern comfort models to estimate occupants’ comfort level in post-war existing buildings, as they do not consider local thermal discomfort [25]. There has been continuous research over recent years to align the energy use in nearly zero-energy buildings (nZEBs) with the expected thermal comfort standards [26]–[28], where an nZEB is defined as a building that has very high energy performance with the nearly zero or very low amount of energy required being covered to a very significant extent by energy from renewable sources [6].

4.3.2 Visual comfort

Poor lighting conditions can cause discomfort. Visual comfort accounts for the occupant's work efficiency in terms of satisfactory lighting conditions. Visual comfort is a subjective measure dependent on certain factors such as illumination, luminance and brightness, luminous spectrum and risk of glare [29]. The presence of a good visual environment can add to the well-being and productivity of the occupants [30]. There are values of illuminance described in the standard EN 12464-1 [31] for work places in buildings that are required to be maintained to fulfil visual comfort and performance needs [31]. A literature survey by Fabi et al. [32] regarded several psychological (attitudes), social (occupancy), physical (direct sunlight) and contextual (orientation) driving forces responsible for visual comfort in the buildings. Occupants find it challenging to maintain good visual comfort as they have varied perception of glare and lighting levels at work places [33]. Due to the ease in measurement and low-cost the illuminance (lux) at the workplace is used as a common metric for the assessment of visual comfort (adequate lighting) in offices however, other illuminance-based metrics such as Spatial
Daylight Autonomy (sDA) and Useful Daylight Illuminance (UDI) correspond to measuring varying lighting conditions over long-term [34].

4.3.3 Acoustic comfort

Acoustic comfort is the presence of a comfortable acoustic environment without any uncomfortable noise [23]. Acoustic comfort is considered a crucial for non-domestic buildings’ IEQ and is generally given high preference in offices and classrooms by occupants [35]–[37]. Occupants’ satisfaction in work-places can be achieved by speech privacy and comfortable sound levels which is identified as the main problem regarding acoustic quality in office workstations [38]. Building elements play a significant role in offering external and internal sound insulation [39]. The indoor system noise criteria of some spaces and buildings are given in terms of A-weighted sound pressure levels (dB(A)) that is used with the instrument-measured sound levels for the relative loudness as perceived by the human ear in EN15251 [14]. These criteria apply to sources from both outside and inside the building so that relative loudness is measured and used to limit the sound pressure levels inside the spaces. Noise levels can exceed these levels in case of occupants opening windows or the operation of HVAC units. Retrofits can enable the reduction of indoor noise, while addressing solutions for thermal comfort and energy efficiency [40]. Noise criteria do not directly relate to energy performance but depend on the opening of fenestrations. For example, to minimise outdoor noise occupants may close windows in summers and this would limit natural ventilation and cooling energy may be required to maintain indoor thermal comfort.

4.3.4 Indoor Air Quality

IAQ is known to have acute and chronic effects on the health of the occupants [41]. It is directly related to the ventilation rates and concentration of pollutants, which in turn are related to Sick Building Syndrome (SBS) [42]. In closed environments, IAQ is related to both chemical and physical causes (carbon oxides, CO and CO₂, environmental tobacco smoke, formaldehyde, volatile organic compounds (VOCs), ventilation rate, temperature, dampness, ionizing and non-ionising radiation) [43]. Provision of outdoor air supply is known to provide acceptable perceived IAQ [44]. The World Health Organisation (WHO) has published indoor air quality guidelines for selected pollutants and their health effects with the target to ensure provision of safer indoor environment [45]. A review of studies on IAQ in schools by Daisy et al. [46] highlighted that classrooms in the study were not adequately ventilated, causing health related
symptoms due to the high concentration of CO$_2$, exposure to volatile organic compounds (VOCs), moulds and microbial VOCs and allergens. Many studies have investigated the influence of indoor carbon dioxide on occupants’ health and perceived air quality [9], [47], [48]. A study on the association of CO$_2$ with occupants’ health in commercial and institutional buildings of 30,000 occupants in about 400 buildings indicated the prevalence of SBS symptoms [49]. CO$_2$ concentration is considered as an indicator of the rate of ventilation per occupant [49]. Since there is no common index for indoor air quality, it can be expressed in terms of required ventilation or CO$_2$ concentrations [14]. A recent study among European countries showed that regulations for IAQ in domestic buildings were not comprehensive and need additional attention as they were recognised to be the most crucial aspect in building codes by the focus countries: Belgium (Brussels Region), Denmark, France, Germany, Italy, Poland, Sweden and the UK (England and Wales) [50].

4.3.5 Overview of IEQ in University buildings

Generally, university campuses and educational establishments are known to consume increasing amounts of energy due to year-round operation and occupancy of offices, library, lecture halls, seminars, conference rooms, and laboratories [51]. Many of the existing buildings in campuses are old and the opportunity for sustainable campus design are limited. However, their energy saving potential can be increased through energy-efficient retrofits, effective energy management, analysis of intrinsic energy consumption patterns and use of renewable energy technology [52], [53]. Retrofits provide opportunity for improving IAQ in buildings and good IAQ is crucial for a high standard of education [46]. Legislation in Ireland and the UK has directed colleges and universities to report their energy use and to introduce initiatives to improve energy efficiency. An IEQ study conducted by Mihai and Iordache [54] on an educational building evaluated the IAQ index and demonstrated that it as a good indicator of comfort, health and operating costs of the building. A summary of studies on IEQ in academic environments is presented in Table 4.2, illustrating the role of IEQ with respect to study/work performance and the evaluation of retrofits. The main findings of the studies indicated that there is a strong association of IEQ with occupant comfort and satisfaction, study/work performance, building condition and energy consumption.

Linkages between environmental conditions and job satisfaction have also been identified in a study of 95 occupants (workstations) at an open-plan office building [55]. However, a recent
study of 167 new or recently retrofitted (<10yrs) office buildings in 8 European countries (Finland, France, Greece, Hungary, Italy, The Netherlands, Portugal and Spain) found that the highest satisfaction rating was given to lighting comfort followed by thermal comfort, noise and air quality [35]. Since there are a number of parameters (e.g. temperature, humidity, mean radiant temperature, CO₂, noise level etc.) involved in the estimation of the IEQ, their interaction adds to the complexity of evaluation for overall comfort in buildings. Research on non-retrofitted schools in Portugal by Almeida and De Freitas [56] identified insufficient comfort and IAQ conditions. An indoor average air temperature of 14.6°C and low ventilation rates accounted for poor IEQ in those schools.

The presented literature highlights the impact of IEQ on occupants in non-domestic buildings. Different methods of data collection were used for predicting the level of IEQ in new and existing buildings. Strong relationships have been established between occupant performance and IEQ. However, limited research is available that investigates the effects of partial or incomplete retrofits in non-domestic buildings on the occupants, whereas, most of it addresses the effects on energy efficiency. The methodology adopted in this research follows EN15251 for the compliance of IEQ.
Table 4.2 Summary of five studies on IEQ evaluation in academic environments

<table>
<thead>
<tr>
<th>Reference</th>
<th>Building/Experiment location</th>
<th>ASHRAE Climate zone</th>
<th>Objectives</th>
<th>Population/Sample size</th>
<th>Data collection method</th>
<th>Analysis</th>
<th>Results</th>
<th>Main findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>[57]</td>
<td>G3 lecture complex, UTM campus, Malaysia</td>
<td>1</td>
<td>Framework identification and evaluation of IEQ</td>
<td>370 occupants (55% females and 45% males)</td>
<td>Measurements of thermal comfort (T, R.H), lighting (Classroom lux levels), noise (educational decibel levels) and IAQ (VOCs, air speed) based on Standard MS1525:2007. Questionnaire survey on thermal, visual and acoustic comfort.</td>
<td>Univariate analysis</td>
<td>Average temperature (23°C) and CO₂ (513ppm) levels met standards but average RH (73%), noise (76.4dB), lux intensity (251 lux) and air speed (0.4m/s) differed from the standard.</td>
<td>Overall quality of IEQ was found to be below standard in classrooms.</td>
</tr>
<tr>
<td>[56]</td>
<td>9 school buildings (2 retrofitted and 7 non-retrofitted), Northern Portugal</td>
<td>4</td>
<td>Evaluation of hygrothermal performance of classrooms</td>
<td>492 occupants</td>
<td>Continuous measurement of Temp. (T), Relative Humidity (R.H), CO₂ and ventilation rates based on ISO 12569 and ASTM E741-00</td>
<td>Descriptive statistics, statistical analysis of variance and ASHRAE graphical method</td>
<td>Non-retrofitted schools have avg. air temp. of 14.9 °C compared to ref. design temp of 20°C and 25 °C for winter and summer. Retrofitted schools had temp. within comfort boundaries. Overheating was observed in summers.</td>
<td>Retrofitted schools were found to be substantially different to non-retrofitted schools.</td>
</tr>
<tr>
<td>[58]</td>
<td>Six buildings, Champs sur Marne, University Campus, France</td>
<td>4</td>
<td>Energy efficiency audit and comfort assessment</td>
<td>610 occupants (158 in offices and 452 in classrooms)</td>
<td>Physical measurements (ISO 7726: 2002), thermal comfort surveys (ASHRAE 55, EN 15251:2007)), indoor air temperature (T), Relative Humidity (R.H) and CO₂ concentration</td>
<td>Analysis using Building Energy Model</td>
<td>Refurbishment operations caused large differences in energy consumption. In summer period classrooms indicate overheating (25% PMV values above category III). IAQ was poor in classrooms (86% measured CO₂ values larger than 800ppm)</td>
<td>Audit method helps in offering reliable retrofitting recommendations reducing energy consumption and improving comfort.</td>
</tr>
<tr>
<td>[27]</td>
<td>Tyree Energy Technologies Buildings, University of New South Wales, Australia</td>
<td>3</td>
<td>Investigate relationship between IEQ and study/work performance</td>
<td>210 occupants</td>
<td>Questionnaire (acceptance of thermal, visual, acoustical comfort and lighting) and archival records used.</td>
<td>Correlation coefficients and multiple linear regressions</td>
<td>Thermal quality, acoustic quality and room/space layout were the main components of IEQ that contribute to study/work performance of occupants</td>
<td>Environment variables and overall environment satisfaction are correlated with occupants’ study/work performance.</td>
</tr>
<tr>
<td>[59]</td>
<td>Classrooms and lecture halls, Hong Kong Polytechnic University</td>
<td>3</td>
<td>Investigate the relationship of IEQ and learning performance in air-conditioned teaching rooms</td>
<td>312 occupants (26% female and 74% male)</td>
<td>Subjective assessments and objective measurements (T, R.H, CO₂, air speed, mean radiant temp., illumination, equivalent sound pressure levels, occupant activity and clothing)</td>
<td>Semantic differential scale and visual analogue scale for subjective evaluation.</td>
<td>84% satisfied with thermal comfort, 76% with IAQ, 91% with visual environment and 90% with aural environment</td>
<td>There is strong association of overall IEQ votes to the learning performance.</td>
</tr>
</tbody>
</table>

Chapter 4. An Indoor Environmental Quality (IEQ) assessment of a partially-retrofitted university building

4.4 Methodology of investigation

4.4.1 Field study

This study was conducted at the National University of Ireland (NUI) Galway located on the west coast of Ireland. Part of the Arts and Science Building, which was built during the 1970’s, was selected for this IEQ study (Figure 4.1). The total floor plan area of the building is 14,136 m², and the field study was conducted in a North-West wing of the building, with an area of 537 m² (Figure 4.3). Galway has a mixed-humid climate classified under category 4A of the ASHRAE international climate zones definitions [60]. Based on historical weather data of Co. Galway from 2014-2017, July is the hottest month with an average dry bulb temperature of 15.3°C and coldest month is February with an average dry bulb temperature of 6.7°C [61]. The wettest month of the year is October with an average of 144.9 mm of rain [61]. Figure 4.2 shows the outdoor dry bulb air temperature and relative humidity of the period (June’16 to June’17) during which the study was conducted, based on the data collected from the weather station installed at NUI Galway campus on the roof of the Arts and Science Building [62].

Figure 4.1 Field study building (with area of study highlighted in the box)
Chapter 4. An Indoor Environmental Quality (IEQ) assessment of a partially-retrofitted university building

Figure 4.2 Outdoor air temperature and relative humidity profile at NUI Galway during June 2016 to June 2017

The field study location was chosen based on the following factors:

- It is the oldest part of the Arts and Science Building and has been partially retrofitted.
- The retrofit is partially completed (ad-hoc) due to initial budget limitations and to minimise the impact on occupants during retrofitting.
- There are no energy-intensive laboratories.
- It is a mixed occupancy building (offices, lecture halls, post-graduate rooms, conference rooms and laboratories).
- The occupancy is generally between 50-60% throughout the academic year.

As shown in Figure 4.3, overall there are 25 occupied zones and two corridors (Ground Floor, First Floor) in the wing of the building considered in this study, including 13 offices (G.0, G.1, G.2, G.4, G.5, G.6, G.7, G.8, G.9, G.10, G.11, G.12, G.18), 2 conference rooms (G.3, G.13), 3 laboratories (G.15, F.5, F.6), 3 post-graduate rooms (G.14, G.16, G.17) and 4 lecture rooms (F.1, F.2, F.3, F.4). The southern part of the department is connected to the rest of the Arts and Science Building through corridors ending with doors.
Chapter 4. An Indoor Environmental Quality (IEQ) assessment of a partially-retrofitted university building

The building is either naturally ventilated without heating (June to September) or with heating (October to May). The university’s CHP (combined heat and power) system meets the heating and electrical energy demand of the building. A baseboard heating loop is present in all the zones and is controlled using local TRVs (thermostatic radiator valves), but the heating schedule is controlled centrally for the building. The building structure was constructed mainly using precast concrete technology and other construction components with materials are shown in Table 4.3.

Out of 27 zones, the façade of 13 zones was retrofitted from single-glazing (metal frame with no thermal break) to double-glazing (metal frame with thermal break) in 2005 (see Figure 4.3). The baseboards heaters were also replaced in all the zones with more efficient units and TRVs were attached to control the indoor temperature manually along with additional insulation in the walls. There was no programmable room thermostat available to control the heating automatically. Therefore, baseboard heaters would continuously function on the predefined schedule for the whole building irrespective of the occupancy in all the zones. All the zones have recessed lighting to maintain workplace illuminance.
Table 4.3 Construction components and their U-values in the Arts and Science Building

<table>
<thead>
<tr>
<th>Construction component</th>
<th>Average U-value</th>
<th>Layers (thickness)</th>
<th>Remarks</th>
</tr>
</thead>
</table>
| Roof                   | 0.54            | Roof membrane (9.5 mm)  
                      |                 | Roof insulation (88 mm)  
                      |                 | Metal Decking (1.5 mm)  
                      |                 | -                   |
| Ceiling                | 3.14            | Mineral fibre board (19 mm)  
                      |                 | All zones           |
| Exterior walls         | 0.26            | Metal panel (5 mm)  
                      |                 | Board insulation (50 mm)  
                      |                 | Rockwool insulation (100 mm)  
                      |                 | Plasterboard (12.5 mm)  
                      |                 | All zones           |
| Interior walls         | 2.57            | Plaster (20 mm)  
                      |                 | Concrete block (100 mm)  
                      |                 | Plaster (20 mm)  
                      |                 | All zones           |
| Single glazing         | 5.79            | --                 | Non-retrofitted zones |
| (metal frame           |                 |                    |         |
| with no thermal break  |                 |                    |         |
| Double glazing         | 1.89            | --                 | Retrofitted zones  
| (metal frame           |                 |                    |         |
| with thermal break     |                 |                    |         |
| First floor            | 4.67            | Linoleum tile (8 mm)  
                      |                 | Concrete dense (300 mm)  
                      |                 | -                   |
| Ground floor           | 2.57            | Linoleum tile (8 mm)  
                      |                 | Screed (75 mm)  
                      |                 | DPC (3 mm)  
                      |                 | Concrete dense (200 mm)  
                      |                 | -                   |
| Doors                  | 2.97            | Wooden panel (25 mm)  
                      |                 | All zones           |

To assess IEQ in the building, short and long-term surveys were conducted over the duration of one year with four seasonal measurements i.e. summer (1st June- 31st Aug), autumn (1st Sep-30th Nov), winter (1st Dec- 28th Feb) and spring (1st Mar- 31st May) of 2016-17. The survey participants included the staff and students of the department that occupies this wing of the building.

4.4.2 Occupant surveys

To conduct the IEQ assessment, a questionnaire was prepared for the staff and students based on guidelines in ASHRAE 55:2013 [21] and the CBE IEQ survey [63]. In a review of ten IEQ survey methods, it was found that the CBE survey had the largest number of occupants in buildings surveyed by ‘right-now’ and long-term evaluations [64]. Therefore, the questionnaire used in the field study was designed based on the CBE IEQ survey. Right-now (Point-in-time surveys) were conducted during the times when the building was occupied, including questions on satisfaction with thermal comfort, visual comfort, acoustic comfort and indoor air quality as a part of short-term analyses. The building users were invited to take part in the surveys during the four seasons as shown in Table 4.4. A total of 83 surveys of the office occupants
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(ground floor) were conducted with the occupants in each season exceeding the 50% occupants criteria [21]. A total 144 surveys among students (on two separate days) were conducted in the lecture room F.2 (first floor) during two full days of normal occupancy.

Table 4.4 PIT survey schedule

<table>
<thead>
<tr>
<th>Seasons</th>
<th>PIT survey dates</th>
<th>No of occupants (% of occupants surveyed)</th>
<th>Floor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer (Jun-Aug)</td>
<td>8th August - 28th August 2016</td>
<td>14 (61)</td>
<td>Ground floor</td>
</tr>
<tr>
<td>Autumn (Sep-Nov)</td>
<td>24th October - 14th November 2016</td>
<td>16 (53)</td>
<td>Ground floor</td>
</tr>
<tr>
<td>Winter (Dec-Feb)</td>
<td>16th January - 10th February 2017</td>
<td>18 (60)</td>
<td>Ground floor</td>
</tr>
<tr>
<td>Spring (Mar-May)</td>
<td>11th April - 9th May 2017</td>
<td>15 (50)</td>
<td>Ground floor</td>
</tr>
<tr>
<td>Autumn (Sep-Nov)</td>
<td>4th October 2016</td>
<td>98 (100)</td>
<td>First floor</td>
</tr>
<tr>
<td>Winter (Dec-Feb)</td>
<td>15th February 2017</td>
<td>46 (100)</td>
<td>First floor</td>
</tr>
</tbody>
</table>

4.4.3 Physical measurements

Physical measurements were conducted for the IEQ variables: indoor air temperature (°C), relative humidity (% RH), mean radiant temperature (°C), air velocity (m/s), illumination (lux), CO₂ (ppm) and noise level (dBA). LASCAR (EL-USB-2+) data loggers [65] were used to measure temperature and humidity profiles of each zone in the Department at 10 minutes interval between 20th June 2016 and 6th June 2017, covering the four (Irish) seasons: summer, autumn, winter and spring.

The short-term evaluation was conducted by using point-in-time measurements together with the occupant surveys (see Section 4.5.2) during working hours (8:00-16:00) for the durations shown in Table 4.4, in the four seasons on the ground floor and twice in the lecture room on the first floor. The parameters (temperature, relative humidity, mean radiant temperature, illumination levels, CO₂ and air velocity) were measured using a Testo-480 portable measuring instrument [66], where measurement probes were placed 1.0 m above the floor near the respondents during normal working hours, based on a Class II field research protocol [67]. Detailed thermal imaging was carried out on the building using a FLIR T335 [68] camera under overcast conditions as per ISO 6781 [69] to determine the potential areas of insulation defects, air leakage, thermal bridging and heat loss in the building. Acoustic comfort was measured using a CEL-450 sound level meter [70] determining the equivalent sound pressure levels during the normal working hours at a few representative locations in the building. A description of the data collection strategy is presented in detail in the Appendix C.
A weather station [62] is located on the roof of the field study building (N53° 16’47” W9° 03’37”') and records weather data at one-minute intervals. The recorded parameters are: dry bulb air temperature, relative humidity, barometric pressure, total and diffuse solar irradiation, wind speed, wind direction, and rainfall.

4.4.4 Calculation of physical parameters

(1) Running mean outdoor air temperatures

In naturally ventilated buildings, to calculate the adaptive comfort ranges during summer, the indoor air operative temperatures are predicted based on a function of the exponentially weighted running mean of the outdoor temperature when the heating system is not in operation [14]. The exponentially-weighted outside running mean temperature accounts for time-dependency over which the occupants adapt to their environment and it is calculated based on Equations (4.1) and (4.2),

\[
t_{rm} = (1 - \alpha)t_{ed-1} + \alpha t_{rm-1}
\]

\[
t_{rm} = \frac{t_{ed-1} + 0.8t_{ed-2} + 0.6t_{ed-3} + 0.5t_{ed-4} + 0.4t_{ed-5} + 0.3t_{ed-6} + 0.2t_{ed-7}}{3.8}
\]

where \( t_{rm} \) is the running mean indoor air operative temperature for today, \( t_{rm-1} \) is the running mean indoor air operative temperature for the previous day, \( t_{ed-1} \) is the daily mean external temperature for the previous day and \( t_{ed-2} \) is the daily mean external temperature for the day before and so on. Here, \( \alpha \) is a constant between 0 and 1, which is recommended as 0.8 for use if the running means are calculated weekly.

The indoor air operative temperature (\( t_{rm} \)) obtained for the rooms using the outdoor air temperature (\( t_{ed} \)) was used to determine the comfort ranges and cross evaluate them based on categories defined in EN 15251 [14] and are shown in Table 4.5.

<table>
<thead>
<tr>
<th>Category</th>
<th>Lower limits</th>
<th>Upper limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>( t_{i,\text{min}} = 0.33t_{rm} + 18.8 - 2 )</td>
<td>( t_{i,\text{max}} = 0.33t_{rm} + 18.8 + 2 )</td>
</tr>
<tr>
<td>II</td>
<td>( t_{i,\text{min}} = 0.33t_{rm} + 18.8 - 3 )</td>
<td>( t_{i,\text{max}} = 0.33t_{rm} + 18.8 + 3 )</td>
</tr>
<tr>
<td>III</td>
<td>( t_{i,\text{min}} = 0.33t_{rm} + 18.8 - 4 )</td>
<td>( t_{i,\text{max}} = 0.33t_{rm} + 18.8 + 4 )</td>
</tr>
</tbody>
</table>

Note: These limits apply when 10 < \( t_{rm} < 30^\circ\text{C} \) for the upper limit and 15 < \( t_{rm} < 30^\circ\text{C} \) for the lower limit.
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(2) PMV and PPD
To determine the physical and contextual conditions in which the thermal environment can be evaluated as acceptable from the point of view of thermal comfort, Fanger performed an experiment on steady state heat transfer model [26]. The comfort equation was derived and expanded into the ASHRAE 55 [21] seven-point thermal sensation scale known as ‘Predicted Mean Vote’ (PMV) index. It has the following range: +3 (hot), +2 (warm), +1 (slightly warm), 0 (neutral), -1 (slightly neutral), -2 (cool) and -3 (cold). The PMV equation is a function of environmental variables as:

$$PMV = f(t_a, t_{mrt}, v, p_a, M, I_{cl})$$  \hspace{1cm} (4.3)

where $t_a$ is air temperature [°C], $t_{mrt}$ is mean radiant temperature [°C], $v$ is relative air velocity [m/s], $p_a$ is humidity (vapour pressure) [kPa], $M$ is metabolic rate [W/m$^2$], and $I_{cl}$ is clothing insulation [clo].

Further, based on the experimental studies on PMV, Fanger developed an empirical relationship of PMV with the ‘Predicted Percentage Dissatisfied’ (PPD) which predicts the percentage of people who feel more than slightly warm or cool [71]. The relationship between PMV and PPD is represented as:

$$PPD = 100 - 95 \exp(-0.03353 X PMV^4 - 0.219 X PMV^2)$$  \hspace{1cm} (4.4)

The PMV-PPD method is applied in the evaluation of thermal comfort taking into account the environmental variables [14]. The thermal comfort at each point of measurement was calculated using Equations (4.3) and (4.4). The recommended values of these indexes and other thermal environment variables is given in Table 4.6.

<table>
<thead>
<tr>
<th>Table 4.6 Recommended values of thermal environment variables and indexes in EN15251 [14]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Indoor air temperature (°C)</strong></td>
</tr>
<tr>
<td>---------------------------------------------------------------</td>
</tr>
<tr>
<td>Recommended ranges -Category III (EN15251)</td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

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(3) Ventilation and infiltration rates

IAQ is generally expressed in terms of CO$_2$ concentration and ventilation required for reducing the concentration of indoor air pollutants [41]. Indoor CO$_2$ is a good indicator of indoor air quality [72] and relationships between CO$_2$ and indoor air quality have been well documented [73]. Calculation of ventilation and infiltration rates in the occupied spaces is crucial in buildings as it directly impacts IAQ. The standards for minimum rates of ventilation are specified in indoor quality standards such as ASHRAE Standard 62 [67] and EN15251 [14]. In the case study building, the exchange of air is possible only through windows (ventilation) and gaps (infiltration) in the building envelope. This field study building is naturally ventilated, and no mechanical ventilation is present. The measurement of ventilation and infiltration rates is possible using steady state or decay methods, where the CO$_2$ generated by the occupant is used as a tracer gas. The measurements of CO$_2$ are taken for ventilation when the occupant is present in the building and for infiltration when the occupant is not present in the building [72], [74], [75]. In this study, the steady state method is used to calculate the ventilation rates when the CO$_2$ concentration has reached equilibrium represented by a constant level of concentration over a time period of 10 to 20 minutes. Therefore, the air change rate ($A_S$) can be calculated based on the average CO$_2$ generation rates [73], [76] (see Equation 4.5).

$$A_S = \frac{6 \times 10^4 n C_p}{V (C_s - C_R)} \quad (4.5)$$

where $A_S$ is the air change rate [$h^{-1}$], $n$ is the number of people in the space, $C_p$ is the average CO$_2$ generation rate per person (generally 0.46 [l.min$^{-1}$] person$^{-1}$]); $V$ is the volume of the room [$m^3$]; $C_s$ is the steady state indoor CO$_2$ concentration [ppm]; $C_R$ is the CO$_2$ concentration in supply air (outdoor air) [ppm]. In steady state methods, it is assumed that the ventilation rate and outdoor CO$_2$ concentration are constant across the time during which the study is carried out.

The infiltration ($f_v$) in 1/s can be calculated based on CO$_2$ concentration decay over the time period when the occupants are not present on the building [72], [74], [75], as given by:

$$f_v = \frac{1}{t} \ln \frac{C_{ia} - C_{st}}{C_{ib} - C_{st}} \quad (4.6)$$
where $f_v$ is the fresh air ventilation rate through infiltration (1/s), $C_{ia}$ is the CO$_2$ concentration at moment $a$ (mg/m$^3$); $C_{ib}$ is the CO$_2$ concentration at moment $b$ (mg/m$^3$); $C_{st}$ is the CO$_2$ concentration in supply air at time $t$ (s) over which the ventilation rate is calculated.

Volume flow of air in the zone can be calculated further by using the relationship in Equation (4.7).

$$q = f_v \cdot V$$  \hspace{1cm} (4.7)

where $q$ is the volumetric airflow in (m$^3$/s), $f_v$ is the infiltration rate (1/s) and $V$ is the volume of the room (m$^3$).

### 4.5 Field study results and discussion

The field study comprised objective (long-term and short-term measurements) and subjective (occupant surveys) evaluations to understand the IEQ conditions inside the building and to assess the effectiveness of ad-hoc and partial retrofit practices. The number of respondents was based on the availability of occupants throughout the year in the offices and lecture rooms. Therefore, under typical occupancy, more than 50% of occupants were surveyed during each of the four seasons to understand the influence of building conditions on their satisfaction and comfort, excluding the lecture rooms, which were occupied only during the academic term.

#### 4.5.1 Thermal environmental conditions: Long-term measurements

Long-term measurements were conducted during working hours to understand the overall profile of indoor thermal environment conditions throughout the study period of one year. The data logger was installed in each room of the building, to record air temperature and relative humidity (RH) at a time step of 10 minutes. A summary of outdoor temperature, humidity, total solar radiation and heating schedule for all the seasons are given in Table 4.7 for the building. The mean and standard deviations of the data recorded during working hours in the building for each season during June 2016 to June 2017 are presented in Table 4.8. The recorded summer mean outdoor temperature was 16.0°C. The measured data for indoor temperature and humidity was found to be within the comfortable limits during the summer period (19-22°C for a Category III building). Natural ventilation is the main mode of operation of the building throughout the year, but heating is only operational during the autumn, winter and spring period.
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Table 4.7 Summary of the outdoor and indoor conditions for the case study building

<table>
<thead>
<tr>
<th></th>
<th>Summer</th>
<th>Autumn</th>
<th>Winter</th>
<th>Spring</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean outdoor temperature [°C] (8:00-16:00)</td>
<td>16.0</td>
<td>11.0</td>
<td>7.7</td>
<td>11.3</td>
</tr>
<tr>
<td>Mean outdoor humidity [%] (8:00-16:00)</td>
<td>83.5</td>
<td>89.6</td>
<td>92.4</td>
<td>74.7</td>
</tr>
<tr>
<td>Total solar radiation [W/m²] (8:00-16:00)</td>
<td>371.6</td>
<td>172.6</td>
<td>83.3</td>
<td>371.4</td>
</tr>
<tr>
<td>Ventilation type</td>
<td>NV</td>
<td>NV &amp; H</td>
<td>NV &amp; H</td>
<td>NV &amp; H</td>
</tr>
<tr>
<td>Heating period</td>
<td>--</td>
<td>15/10/16-31/11/16</td>
<td>1/12/16-28/02/17*</td>
<td>1/03/17-14/05/17</td>
</tr>
<tr>
<td>Daily heating schedule</td>
<td>--</td>
<td>Mon-Sat</td>
<td>Sun</td>
<td>Mon-Fri</td>
</tr>
<tr>
<td></td>
<td>08:00-22:00</td>
<td>08:00-13:00</td>
<td>08:00-22:00</td>
<td>08:00-17:00</td>
</tr>
</tbody>
</table>

Note: NV= Natural Ventilation; H= Heating
*Heating is turned off for the Christmas vacation period

The autumn season had a mean outdoor temperature of 11.0°C during office hours. The monitored data indicates that some zones (G.1, G.10, G.11, G.12, G.13, F.4, F.6, FF corridor) presented in Table 4.8 have their seasonal mean indoor temperature below the recommended limits as per EN15251 (19°C), even while the rooms were being heated as per the heating schedule in Table 5.2. This may be due to the inability of envelope to retain heat inside the zones, although G.1, G.12, G.13, F.4 and F.6 were retrofitted with double-glazing. Due to low average total solar radiation of 172.6 W/m² in autumn, the impact of external gains through glazing can be assumed relatively low. Zones G.11 (NR) and G.12 (R) have similar area and orientation (NW) and they have higher standard deviation in autumn air temperature compared to others, which can be attributed to the large glazing surface (94%) on the exposed envelope in these two zones, leading to greater indoor temperature fluctuations. However, the mean for relative humidity in autumn is among the highest in both the zones, which suggests that the occupants either kept the windows frequently open during office hours or may have other sources of humidity compared to others. Lower autumn mean indoor temperature of 17.3°C in zone G.11 compared to 18.5°C in zone G.12 may be due to presence of old single-glazed façade and/or increased ventilation. Zone G.13 (conference room) is not constantly occupied and a low standard deviation for humidity reflects that the windows were not frequently opened for natural ventilation. However, the mean humidity level is highest in this zone compared to other zones that may be due to internal moisture generation (room used as a staff room/tea room). Occupant behaviour could be the reason for the high indoor humidity.
<table>
<thead>
<tr>
<th>Room</th>
<th>Type of room</th>
<th>Glazing &amp; Orientation</th>
<th>Status</th>
<th>Indoor air temperature (°C)</th>
<th>Indoor relative humidity (% RH)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Summer Mean</td>
<td>Autumn</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Mean</td>
<td>Stdev.</td>
</tr>
<tr>
<td>G.0</td>
<td>Single office</td>
<td>Double (SW)</td>
<td>R</td>
<td>203</td>
<td>0.8</td>
</tr>
<tr>
<td>G.1</td>
<td>Single office</td>
<td>Double (SW)</td>
<td>R</td>
<td>205</td>
<td>0.9</td>
</tr>
<tr>
<td>G.2</td>
<td>Single office</td>
<td>Single (SW)</td>
<td>NR</td>
<td>205</td>
<td>1.1</td>
</tr>
<tr>
<td>G.3</td>
<td>Conference room</td>
<td>Single (SW)</td>
<td>NR</td>
<td>198</td>
<td>1.3</td>
</tr>
<tr>
<td>G.4</td>
<td>Single office</td>
<td>Single (SW)</td>
<td>NR</td>
<td>191</td>
<td>0.9</td>
</tr>
<tr>
<td>G.5</td>
<td>Single office</td>
<td>Single (SW)</td>
<td>NR</td>
<td>200</td>
<td>1.0</td>
</tr>
<tr>
<td>G.6</td>
<td>Single office</td>
<td>Single (SW)</td>
<td>NR</td>
<td>201</td>
<td>0.9</td>
</tr>
<tr>
<td>G.7</td>
<td>Single office</td>
<td>Double (SW)</td>
<td>R</td>
<td>212</td>
<td>1.1</td>
</tr>
<tr>
<td>G.8</td>
<td>Single office</td>
<td>Single (SW)</td>
<td>NR</td>
<td>200</td>
<td>1.3</td>
</tr>
<tr>
<td>G.9</td>
<td>Single office</td>
<td>Single (SW)</td>
<td>NR</td>
<td>209</td>
<td>2.1</td>
</tr>
<tr>
<td>G.10</td>
<td>Single office</td>
<td>Single (SW)</td>
<td>NR</td>
<td>197</td>
<td>1.2</td>
</tr>
<tr>
<td>G.11</td>
<td>Single office</td>
<td>Single (NW)</td>
<td>NR</td>
<td>186</td>
<td>1.6</td>
</tr>
<tr>
<td>G.12</td>
<td>Single office</td>
<td>Single (NW)</td>
<td>NR</td>
<td>190</td>
<td>0.9</td>
</tr>
<tr>
<td>G.13</td>
<td>Conference room</td>
<td>Single (NE)</td>
<td>NR</td>
<td>196</td>
<td>0.8</td>
</tr>
<tr>
<td>G.14</td>
<td>Open plan office</td>
<td>Double (NE)</td>
<td>R</td>
<td>207</td>
<td>1.0</td>
</tr>
<tr>
<td>G.15</td>
<td>Computer lab</td>
<td>Single (NE)</td>
<td>NR</td>
<td>215</td>
<td>1.5</td>
</tr>
<tr>
<td>G.16</td>
<td>Open plan office</td>
<td>Double (NE)</td>
<td>R</td>
<td>213</td>
<td>0.9</td>
</tr>
<tr>
<td>G.17</td>
<td>Single office</td>
<td>Single (NE)</td>
<td>NR</td>
<td>211</td>
<td>1.2</td>
</tr>
<tr>
<td>G.18</td>
<td>Single office</td>
<td>Single (NE)</td>
<td>NR</td>
<td>201</td>
<td>0.9</td>
</tr>
<tr>
<td>GF</td>
<td>Corridor</td>
<td>-</td>
<td>-</td>
<td>202</td>
<td>0.7</td>
</tr>
</tbody>
</table>

**Note:** SW - South West, NW - North West, NE - North East, R - Retrofit, NR - Non-Retrofit
During winter, there was a mean outdoor temperature of 7.7°C. The mean indoor temperatures of the retrofitted zones (G.1, G.12, F.3, F.4, F.5, F.6, FF corridor) are well below the recommended limits, as can be seen in Table 4.8. Retrofitted lecture rooms (F.3, F.4) have recorded lower mean indoor temperatures in winters which indicates the ineffectiveness of the envelope to maintain comfortable temperatures despite having a dedicated heating schedule (Table 4.7). During winters, windows were generally closed during office hours in the building; however, the labs F.5 and F.6 were naturally ventilated frequently, which is also indicated with the higher standard deviations in indoor temperatures and indoor relative humidity. Again, zone G.11 (NR) recorded the lowest mean indoor temperature and higher standard deviation which suggests that higher percentage of single-glazing in the room leads to a greater heat loss in winters and indoor temperature fluctuations. Since weather conditions during winters are mostly overcast, with an average total solar radiation received of 83.3 W/m², it may be deduced that orientation of the rooms did not have any major impact as external gains through the glazing would be relatively low in winters.

During the spring period, the heating was operational, and occupants also regulated internal temperatures by natural ventilation or TRVs. The mean outdoor temperature recorded during the spring period was 11.3°C. However, as can be seen in Table 4.8, the mean indoor air temperatures were above 22°C in 9 zones. EN15251 recommends provision of cooling above these indoor temperatures. However, since the heating was operational during this period in the building, improved management of the heating schedule could minimise overheating indoor temperatures as the outdoor spring temperatures are higher compared to winters. Also, a considerable external solar gain (mean total solar radiation 371.4 W/m²) through glazing may have led to raised indoor temperatures, especially to SW orientated zones (G.0, G.5, G.7, G.9, F.1, F.2) with the mean between 22.3-22.8°C. This is also supported by the fact that these zones have higher standard deviation compared to NW orientation zones. Another factor that may be responsible for the overheating was the provision of double-glazing and infrequent opening of windows in zones G.0, G.7, F.1 and F.2 during this period in conjunction with external solar gain. The windows were generally kept closed in all the zones during spring period, which is indicated by lower mean indoor humidity levels as compared to the outdoor average of 74% and lower standard deviations.

A thermal audit was conducted in winter in accordance with ISO 10878:2013 [77]. The audit indicated severe heat loss through the building façade, especially through the single-glazed
façade and thermal bridges which reinforces the previously discussed results. Figure 4.4 shows the thermal images of the building where loss of heat is minimised on the first floor by double glazing, and partially on the ground floor (where some zones are single glazed). It is also evident from indoor monitoring results (Table 4.8) that significant overheating of spaces occurs during the spring when the heating is operational, while natural ventilation is used by occupants to adapt for their comfort with colder outdoor temperatures.

Figure 4.4 Thermal images of the building envelope (08/12/2016)

The indoor relative humidity levels were generally found to be higher during the summer period since the climate is generally humid in Galway and natural ventilation balances the moisture levels with the outside. The relative humidity is not known to have an impact on thermal comfort, but it is found to be associated with perceived air quality as high humidity levels can cause increase microbiological growth and discomfort [78]. In this study, the mean indoor relative humidity was found to be within the recommended limits (Table 4.8).

4.5.2 Point-in-time survey and measurements

Short-term objective and subjective IEQ assessments (known as Point-in-Time surveys) were conducted as described in Section 4.4.2. The evaluation consisted of point-in-time measurements along with the occupant satisfaction surveys during working hours in the four seasons on the ground floor of the field study building and two times in the lecture room on the first floor. The parameters (temperature, relative humidity, mean radiant temperature, illumination levels, \( \text{CO}_2 \), air velocity and noise levels) were measured using a portable measuring instrument. The collected data is used to analyse the indoor environmental conditions in terms of thermal comfort, visual comfort, acoustical comfort and indoor air quality.
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(1) Thermal comfort (PMV/PPD)

The PMV results (Figure 4.5a), estimated from measured IEQ parameters along with physical parameters of metabolic rate and clothing that were recorded during the point-in-time surveys, are compared with the Thermal Sensation Votes (TSV) from the satisfaction survey responses (Figure 4.5b). The PMV results of 83 point-in-time surveys from the ground floor zones indicate that during all the seasons the mean of PMV lies within the range -0.7 to 0.7 (Figure 4.5a), satisfying the criteria from EN15251 under Category III (see Table 4.6). However, in Figure 4.6 the individual data points of 83 surveys shows the seasonal variation of PMV and PPD outside the recommended comfort zone indicating higher percentage dissatisfaction in some zones with the indoor thermal conditions. During the winter period, the calculated PMV indicates slightly warm comfort sensation whereas mean of TSVs also highlight slightly warm conditions in the zones which may be due to occasional overheating of spaces.

![Figure 4.5 (a) Calculated PMV results, and (b) Thermal Satisfaction Votes (TSVs) for ground floor zones (n=83)](image)

![Figure 4.6 A distribution of 83 data points for ground floor PMV and PPD values](image)
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The mean PMV results from summer, autumn and spring are below 0 (neutral sensation) and the mean Thermal Sensation Votes (TSVs) from the satisfaction survey (Figure 4.5b) are above 0 (neutral satisfaction) which means that the occupants prefer and are satisfied with lower temperatures. The summary of thermal environment variables for all the surveys is given in Table 4.9. It can be noted from the average clothing insulation values of the occupants in autumn, winter and spring are below average for cool conditions (1 clo) [21] and the occupants have adapted themselves and feel comfortable to relatively lower temperatures than suggested in the standard EN15251.

*based on mean ranges from Table 4.8

Two separate surveys were also conducted with students in the lecture room (F.2) during regular teaching in October 2016 and February 2017 with a total of 144 students. The mean of TSVs (Figure 4.7) indicated that the room was warmer in February than October and outside the recommended comfort criteria, which may be due to overheating of rooms especially in winters.

<table>
<thead>
<tr>
<th>Thermal variables</th>
<th>environment</th>
<th>Summer</th>
<th>Autumn</th>
<th>Winter</th>
<th>Spring</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air temperature(°C)* (8:00-16:00)</td>
<td>18.6 - 21.5</td>
<td>17.0 - 21.3</td>
<td>15.2 - 22.5</td>
<td>17.0 - 22.8</td>
<td></td>
</tr>
<tr>
<td>Relative humidity (%RH)* (8:00-16:00)</td>
<td>56.9 - 67.7</td>
<td>50.2 - 72.4</td>
<td>37.9 - 66.6</td>
<td>41.1 - 59.5</td>
<td></td>
</tr>
<tr>
<td>PMV</td>
<td>-1.30 – 0.86</td>
<td>-2.35 – 1.08</td>
<td>-1.42 – 1.08</td>
<td>-1.35 – 0.87</td>
<td></td>
</tr>
<tr>
<td>PPD (5.0% - 40.3%)</td>
<td>(5.3% - 89.8%)</td>
<td>(5.0% - 46.6%)</td>
<td>(5.0% - 43.2%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average clothing insulation (clo)</td>
<td>0.66</td>
<td>0.71</td>
<td>0.76</td>
<td>0.81</td>
<td></td>
</tr>
<tr>
<td>Occupants metabolic rate (met)</td>
<td>1.0 – 1.9</td>
<td>1.0 – 2.1</td>
<td>1.0 – 1.9</td>
<td>1.0 – 2.0</td>
<td></td>
</tr>
<tr>
<td>Occupants gender</td>
<td>Male- 29, Female- 54</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Occupants age range (yr.)</td>
<td>24– 59</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.9 Thermal environment variables during PIT survey for all ground floor zones
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The schedule of heating system (Section 4.5.1) which is common for all the zones may have caused overheating specially in lecture rooms (retrofitted) as the occupants (students) are there for shorter period and does not regulate the TRVs regularly.

However, by comparing the PMV box plots for retrofitted and non-retrofitted zones in Figure 4.8 highlights that there are wider ranges of PMVs in non-retrofitted zones than retrofitted zones, indicating higher seasonal discomfort levels in non-retrofitted zones. This may be due to the poor insulating properties and higher infiltration of the single-glazed façade compared to the double-glazed façade, leading to larger indoor temperature variations in general.

During the summer season, heating is not operational, and the building is only naturally ventilated. As PMV has been found to underestimate the range of comfort in summer, the adaptive comfort model is used to assess the thermal neutrality of the occupants. As per EN15251[14], the adaptive comfort models are based on relationships between the outdoor and indoor temperatures and they already consider the occupants clothing and metabolic levels.
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The occupants can regulate the thermal conditions only by operating the windows and adjusting their clothing. The ranges of acceptability (operative temperatures) are plotted for the building against the prevailing mean outdoor air temperatures between 10-32.5 ºC. The mean outdoor air temperature recorded in summer season was 16.0 ºC. There are three bands for acceptability (1) 60% acceptability (a wider band of acceptable operative temperatures)- Category III (2) 80% acceptability (a narrow band of acceptable air temperatures)- Category II and (3) 90% acceptability (a very narrow band of acceptable air temperatures for higher standard of thermal comfort)- Category I. The ground floor zones were found to be within the 90% acceptability limits with some in 80% acceptability band that correspond to occasional overheating during the summer period in those zones (see Figure 4.9).

![Graph showing operative temperature against outdoor temperature bands]

Figure 4.9 Adaptive comfort chart for summer season (ground floor zones of the case study building)

(2) Visual comfort

The measured average levels of work plane illuminance (also known as lighting environment) during working hours are given in Table 4.10 for the four seasons for zones with different orientations and occupancy types. The measured values generally satisfy or exceed the recommended minimum work plane illuminance (natural/artificial) given in EN15251 for typical occupancy zones (see Table 4.10).
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Table 4.10 Measured work plane illuminance average values in working hours during PIT surveys

<table>
<thead>
<tr>
<th>Zones</th>
<th>Floor area (m²)</th>
<th>Orientation</th>
<th>Recommended range: Category III EN15251 (lux)</th>
<th>Workplace illuminance (lux)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Summer</td>
<td>Autumn</td>
</tr>
<tr>
<td>Single office (G.2)</td>
<td>12.2</td>
<td>SW</td>
<td>500</td>
<td>720</td>
</tr>
<tr>
<td>Single office (G.7)</td>
<td>18.2</td>
<td>SW</td>
<td>500</td>
<td>512</td>
</tr>
<tr>
<td>Single office (G.18)</td>
<td>18.0</td>
<td>NE</td>
<td>500</td>
<td>703</td>
</tr>
<tr>
<td>Open plan office (G.14)</td>
<td>34.8</td>
<td>NE</td>
<td>500</td>
<td>385</td>
</tr>
<tr>
<td>Conference room (G.3)</td>
<td>30.5</td>
<td>SW</td>
<td>500</td>
<td>-</td>
</tr>
<tr>
<td>Lecture room (F.2)</td>
<td>74.0</td>
<td>SW</td>
<td>500</td>
<td>-</td>
</tr>
</tbody>
</table>

The absence of any external shading system and the presence of approximately 90% glazing in all the zones for daylighting. Although, the required level of lighting was primarily maintained by artificial lighting in the zones during all the seasons as the conditions are mainly cloudy (low solar radiation) as discussed in Section 4.5.1. During the retrofitting, the glazing ratio was maintained similar to the original façade and the only protection against glare are the internal vertical blinds. The results of all the surveyed ground floor zones (Figure 4.10a) and lecture room F.2 (Figure 4.10b) indicate that the occupants were satisfied with the workplace illumination levels in all the zones.

Figure 4.10 Lighting satisfaction survey results for (a) the ground floor zones (n=83) and (b) lecture room F.2 (n=144)

(3) Acoustic comfort
To analyse the building’s indoor acoustic environment, limits on equivalent continuous weighted sound pressure level (L_{eq}) were measured once in each typical zone of different type
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of occupancy (office, conference room and lecture room) during working hours (see Table 4.11). $L_{eq}$ is often described as the average noise level (outdoor and indoor) during a noise measurement period. The $L_{eq}$ value was set by averaging the sound pressure levels for 2 hours and then defining the average as a representative value on a 2-hour basis due to equipment limitations. Therefore, unnecessary noise data could be minimised.

Table 4.11 Measured physical value for acoustic comfort

<table>
<thead>
<tr>
<th>Zones</th>
<th>Recommended criteria Category III-EN15251 dB(A)</th>
<th>Average of equivalent sound level - $L_{eq}$ dB(A)</th>
<th>Range of equivalent sound level LF$<em>{mn}$- LF$</em>{mx}$ dB(A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single office (G.12)</td>
<td>30-40</td>
<td>61</td>
<td>26.9- 109.3</td>
</tr>
<tr>
<td>Open plan office (G.17)</td>
<td>30-40</td>
<td>44.1</td>
<td>28.6- 76.9</td>
</tr>
<tr>
<td>Conference room (G.3)</td>
<td>30-40</td>
<td>49.4</td>
<td>34.5- 90.6</td>
</tr>
<tr>
<td>Lecture room (F.2)</td>
<td>30-40</td>
<td>54.3</td>
<td>29.6- 88.8</td>
</tr>
</tbody>
</table>

Table 4.11 shows the weighted average of equivalent sound levels and the range of equivalent sound levels in representative rooms measured during the sampling period. The average of $L_{eq}$ was found a little above the 40 dB(A) threshold limits, which indicates higher sound pressure levels and, therefore, creates some discomfort to the occupants. The survey results in Figure 4.11a and Figure 4.11b suggest that there is mixed perception towards acoustical satisfaction, but neutral or higher level of satisfaction were observed throughout the year.

Figure 4.11 Acoustical satisfaction survey results, (a) ground floor zones (n=83), and (b) lecture room F.2 (n=144)
(4) Indoor Air Quality

The measurements of CO₂ levels were conducted while the point in time surveys were carried out and the data were recorded in the occupied zones during working hours as per the schedule described in Section 4.4.2. The survey results for the ground floor zones in Figure 4.12a show relative satisfaction with the IAQ in each season. Similarly, the IAQ satisfaction results for the lecture room were closer to a neutral satisfaction (Figure 4.12b). However, peak values were recorded higher than 1000ppm. Several studies have found that CO₂ concentrations above 1000 ppm results in discomfort among approximately 20% of occupants [72].

![Figure 4.12 IAQ satisfaction survey results (a) ground floor zones (n=83), and (b) lecture room F.2 (n=144)](image)

Table 4.12 Measured physical value of CO₂ for indoor air quality in typically occupied zones during working hours

<table>
<thead>
<tr>
<th>Zones</th>
<th>Retrofit Status</th>
<th>Recommended Criteria, Category II EN15251 (ppm)</th>
<th>CO₂ concentration (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Summer</td>
</tr>
<tr>
<td>Single office (G.7)</td>
<td>R</td>
<td>500-800</td>
<td>442-652</td>
</tr>
<tr>
<td>Single office (G.8)</td>
<td>NR</td>
<td>500-800</td>
<td>412-558</td>
</tr>
<tr>
<td>Single office (G.18)</td>
<td>NR</td>
<td>500-800</td>
<td>435-717</td>
</tr>
<tr>
<td>Open plan office (G.14)</td>
<td>R</td>
<td>500-800</td>
<td>373-614</td>
</tr>
<tr>
<td>Lecture room (214)</td>
<td>R</td>
<td>500-800</td>
<td>-</td>
</tr>
</tbody>
</table>

Note: R=Retrofitted; NR= Non-retrofitted

The range of CO₂ levels recorded in the typically occupied zones (single office, open plan office, and lecture room), including both retrofitted and non-retrofitted zones, are given in

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Table 4.12. The concentration of CO$_2$ was measured at higher levels in autumn and winter seasons, which may be a result of inadequate ventilation. There is a direct correlation of CO$_2$ levels with the rate of ventilation or infiltration; this is investigated in more detail in the next section.

**Ventilation and infiltration rates**

Indoor CO$_2$ is used for the calculations as a tracer gas in different zones during all seasons. The case study building is without mechanical ventilation and the fresh air ventilation is a combination of airflow through windows (purge ventilation) and infiltration (gap ventilation) or infiltration alone during unoccupied hours. In Table 4.13, the ventilation rates are calculated for typical retrofitted and non-retrofitted zones and the results indicate that most of the zones do not meet the 4 l/s/person requirement [14]. However, calculated ventilation rates were much below the recommended design value. Infiltration rates calculated using Equation (6) \{Section 4.4.4 (3)\} during unoccupied hours highlighted that retrofitted zones were less leaky compared to the zones with non-retrofitted façade. This, in turn, impacted the IAQ with the increase in the concentration of CO$_2$ affecting occupant health and comfort in absence of ventilation. During the unoccupied period, the CO$_2$ concentration exhibited strong dependence on time owing to steady leakage rate. Some zones were leakier than the other; therefore, based on linear regression of the CO$_2$ and time, their coefficient of determination was calculated as in the Table 4.13. Close fit was observed in the data points between the CO$_2$ decay and time with the trendlines. The infiltration rates were used to calculate the airflow for each zone using Equation (7) \{Section 4.4.4 (3)\} to determine the uncontrolled fresh air supply through infiltration. Based on the results, the field study building does not satisfy the criteria from EN15251 under category III, therefore indicates poor IAQ with insufficient air exchange.

Overall, the impact of ad-hoc and partial retrofitting of the post-war building had varied impacts on the IEQ of the field study building. The data on thermal comfort highlighted that the occupants have preference for lower temperatures represented through PMV and TSVs results in Section 4.5.2 (1). Summer season was most comfortable based on the adaptive comfort plot. The values of PPD were outside the recommended criteria given in the standards and indicate a higher percentage of dissatisfaction in all the zones. Since the workplace illuminance was maintained through artificial lighting throughout the annual period, the occupants were generally satisfied, as shown in Section 4.5.2 (2). Acoustical comfort evaluation in Section 4.5.2 (3) suggests that the average equivalent decibel levels were higher
than recommended, but the occupants felt comfortable, in general, as shown in the satisfaction survey results. Inadequate ventilation rates in the zones resulted in increased CO$_2$ concentration during working hours. Infiltration rates were found to be higher in non-retrofitted zones compared to retrofitted ones, which also corresponds to the lower indoor temperatures during winters while the ventilation is limited.

Table 4.13 Calculated ventilation and infiltration rates for zones with Retrofitted (R) and Non/retrofitted façade (NR)

<table>
<thead>
<tr>
<th>Zone</th>
<th>Area (m$^2$)</th>
<th>Retrofit status</th>
<th>Season</th>
<th>Occupants (n)</th>
<th>Ventilation rates during occupied hours [l/s/person]</th>
<th>Airflow due to infiltration [m$^3$/h]</th>
<th>Coefficient of determination ($R^2$) for CO$_2$ concentration vs Time plots</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single office</td>
<td>12.6</td>
<td>R</td>
<td>Summer</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>(G.0)</td>
<td></td>
<td></td>
<td>Autumn</td>
<td>1</td>
<td>2.14</td>
<td>0.0027</td>
<td>0.9246</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Winter</td>
<td>1</td>
<td>1.54</td>
<td>0.0041</td>
<td>0.9013</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Spring</td>
<td>1</td>
<td>2.42</td>
<td>0.0068</td>
<td>0.8652</td>
</tr>
<tr>
<td>Single office</td>
<td>12.2</td>
<td>NR</td>
<td>Summer</td>
<td>1</td>
<td>2.12</td>
<td>0.0043</td>
<td>0.9614</td>
</tr>
<tr>
<td>(G.2)</td>
<td></td>
<td></td>
<td>Autumn</td>
<td>1</td>
<td>6.20</td>
<td>0.0050</td>
<td>0.8954</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Winter</td>
<td>1</td>
<td>2.48</td>
<td>0.0060</td>
<td>0.8174</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Spring</td>
<td>1</td>
<td>8.45</td>
<td>0.0076</td>
<td>0.8817</td>
</tr>
<tr>
<td>Single office</td>
<td>18.2</td>
<td>R</td>
<td>Summer</td>
<td>1</td>
<td>2.72</td>
<td>0.0099</td>
<td>0.7861</td>
</tr>
<tr>
<td>(G.7)</td>
<td></td>
<td></td>
<td>Autumn</td>
<td>1</td>
<td>2.20</td>
<td>0.0109</td>
<td>0.8954</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Winter</td>
<td>1</td>
<td>1.89</td>
<td>0.0099</td>
<td>0.8865</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Spring</td>
<td>1</td>
<td>2.07</td>
<td>0.0113</td>
<td>0.7200</td>
</tr>
<tr>
<td>Single office</td>
<td>18.6</td>
<td>NR</td>
<td>Summer</td>
<td>1</td>
<td>3.08</td>
<td>0.0116</td>
<td>0.8247</td>
</tr>
<tr>
<td>(G.8)</td>
<td></td>
<td></td>
<td>Autumn</td>
<td>1</td>
<td>1.85</td>
<td>0.0121</td>
<td>0.7245</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Winter</td>
<td>1</td>
<td>3.68</td>
<td>0.0126</td>
<td>0.7309</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Spring</td>
<td>1</td>
<td>1.27</td>
<td>0.0131</td>
<td>0.7869</td>
</tr>
<tr>
<td>Open plan office</td>
<td>54.2</td>
<td>R</td>
<td>Summer</td>
<td>3</td>
<td>2.64</td>
<td>0.0118</td>
<td>0.8737</td>
</tr>
<tr>
<td>(G.16)</td>
<td></td>
<td></td>
<td>Autumn</td>
<td>3</td>
<td>2.44</td>
<td>0.0132</td>
<td>0.9915</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Winter</td>
<td>4</td>
<td>0.76</td>
<td>0.0176</td>
<td>0.9289</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Spring</td>
<td>3</td>
<td>0.82</td>
<td>0.0191</td>
<td>0.9214</td>
</tr>
<tr>
<td>Lecture room</td>
<td>73.9</td>
<td>R</td>
<td>Summer</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>(F.2)</td>
<td></td>
<td></td>
<td>Autumn</td>
<td>41</td>
<td>4.20</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Winter</td>
<td>22</td>
<td>4.00</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Spring</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

4.6 Conclusion

This year-long post-occupancy evaluation of a partially retrofitted university building yielded interesting results. The assessment of the post-war university building was carried out to understand the issues related to the IEQ (thermal comfort, visual comfort, acoustic comfort and indoor air quality) in the building and the impact of ad-hoc retrofit on it. Occupants were
Chapter 4. An Indoor Environmental Quality (IEQ) assessment of a partially-retrofitted university building

satisfied with slightly cool temperatures compared to the mean PMV results, which indicated the adaptation of occupants to slightly cool thermal comfort conditions with low clothing insulation mainly due to the social influence or behaviour. This could potentially affect the selection of retrofit interventions like managing lower setpoint preferences for indoor thermal comfort conditions. A contrast was observed in the mean PMV results of the zones with non-retrofitted façade compared to retrofitted zones, showing a wider range mainly due to seasonal discomfort caused by single-glazed façade. Thermal neutrality was assessed with an adaptive comfort model in summer and most of the occupants experienced 80-90% acceptability for thermal comfort as the outdoor temperatures are comfortable in Galway. Indoor operative temperatures were strongly related to the outdoor running mean temperatures, establishing strong correlation between natural ventilation and occupant comfort. Replacement of single-glazing with double-glazing alone was a poor retrofit selection, as discussed in the results with regard to occupant thermal comfort; however, it may have made an impact on energy consumption which requires further investigation as thermal imaging highlighted improvement in conduction of building façade and reduction in thermal bridges. Overheating in Spring was a common problem as observed from the data collected and can be reduced through appropriate retrofit measures such as regulating heating schedules and adequate mechanical ventilation.

The workplace illuminance levels are maintained with artificial lighting during working hours. Therefore, greater satisfaction was found with visual comfort in the study due to highly glazed façade. Acoustic comfort was found to be within the recommended limits for offices and lecture rooms and higher comfort may be a result of low outdoor noise and the building’s riverside location. Inadequate ventilation caused the indoor air quality to deteriorate in many zones during autumn, winter and spring seasons. A steady-state method was used to calculate the fresh air ventilation rates, but the results showed a deficiency of fresh air in the occupied zones and higher CO₂ concentrations. Partial retrofit of the building was responsible for achieving better airtightness (infiltration) in few zones and it also impacted the thermal comfort of occupants but IAQ was not improved due to inadequate ventilation.

Therefore, it can be concluded that most of the occupants in the building experience their greatest levels of thermal discomfort in the winter season. The lack of a holistic approach to retrofits is a barrier to realising the full benefits of better indoor comfort. This can be addressed through better-planned assessments of buildings before retrofits that can aid in more effective decision making. A more systematic standards-based methodology could have identified the
issues before implementing the retrofit in the field study building with adequate assessment of risk to human health, building fabric, and energy savings. Based on the results of this study thermal comfort and IAQ were the main contributors to the IEQ of the field study building. This study enhanced our understanding of assessing the relationship of IEQ and the ad-hoc retrofitting of façade of a post-war non-domestic building, its functioning and the factors which affect the indoor comfort levels. This field-study added to the database of IEQ studies by investigating thermal comfort expectations of occupants in an educational building in temperate-oceanic climate that was absent in literature. It also highlighted that these expectations are different to those mentioned for existing buildings in the standards. The results can help to guide the development of retrofitting strategies that seek to provide satisfactory IEQ to occupants and avoid partial retrofitting measures for non-domestic buildings. Further research is required to correlate IEQ and the energy performance to thoroughly inform optimal retrofitting strategies such as establishing retrofitting guidelines for existing non-domestic buildings (>35 years) based on field studies that benchmark the impact on both IEQ and energy performance.

4.7 References


Chapter 4. An Indoor Environmental Quality (IEQ) assessment of a partially-retrofitted university building


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Chapter 5: An energy model calibration methodology and application with sensitivity analysis for a partially-retrofitted university building

Chapter 5. An energy model calibration methodology and application with sensitivity analysis for a partially-retrofitted university building

5.1 Chapter overview

This chapter presents the development of a calibrated building energy model using the field-study conducted in Chapter 4. A novel automated-calibration methodology is presented using multi-objective genetic algorithm (GA) and uncertainty analysis. The dynamic building energy model was developed using the audit data (e.g. geometrical, thermo-physical and energy data) together with detailed equipment, lighting and occupant loads, schedules and weather files. The model was then calibrated and validated using energy consumption and indoor air temperature data. The collected data from the field-study between June 2016 – May 2017 were used to develop, calibrate and validate the model for evaluation of deep-retrofit strategies presented in the next chapter. Appendix E contains information on schedule inputs and energy rates and heat gain fractions considered while the model was developed.

Reduction of performance gap in existing building simulation plays a key role in determination of impact of different retrofit strategies. Thus, developing robust calibration methodology is essential to support retrofit decision-making, particularly for non-domestic buildings. In this work, due to high uncertainty in existing building performance, initial sensitivity analysis was conducted using a large set of input parameters (e.g. conductivity, u-value, setpoints, infiltration rate etc.). A genetic algorithm was used in a two-stage automated-calibration to tune the top-ranked parameters. In the first stage, monthly utility data was used for calibration and the acceptance criteria were nearly achieved; however, the analysis of indoor temperatures did not meet the acceptance criteria. Therefore, in the second stage of the calibration measured indoor temperature data (collected during the field-study presented in Chapter 4) were used for further calibration until the criteria was achieved. Additional validation of the model was conducted using a new weather dataset (May 2017 – April 2018). The calibration scripts are presented in Appendix F and a sample of EnergyPlus text file is given in Appendix G. Once validated the model was used to apply different retrofit measures and identify optimal deep-retrofit solution packages (Chapter 6).

This chapter has been submitted to the international journal ‘Building and Environment’ and is under review. Sheikh Zuhaib developed the concept, conducted simulations, interpreted the data and wrote the manuscript. Primary supervisor Dr. Jamie Goggins directed this research and gave feedback on the manuscript at all stages. Dr. Magdalena Hajdukiewicz gave her support and advice on the calibration method.
Chapter 5. An energy model calibration methodology and application with sensitivity analysis for a partially-retrofitted university building

Abstract

Deep-retrofit planning for non-domestic buildings demands high accuracy in energy modelling prediction that minimises the gap between actual and simulated scenarios. A large set of interacting variables and uncertainties in energy performance modelling causes perturbations that can be minimised via automated energy model calibration. A novel multi-stage automated calibration methodology was developed using a case study of a partially-retrofitted university building (>35 yrs. old) in Ireland. Due to higher number of uncertainties in the model, a sensitivity analysis was conducted on the model that is both calibrated and validated as per ASHRAE Guide 14 indices of Cv(RMSE) and NMBE. The calibration process was automated using the optimisation algorithm NSGA-II. Two sets of reference data i.e. (i) monthly utility (heating and electrical energy consumption), and (ii) hourly indoor air temperature were used to conduct calibration in two-stages. Results demonstrate that using only utility data for calibration did not result in accurate predictions of the thermal environment; thus, a second stage was used to improve the model prediction giving a $C_v(RMSE)_{\text{hourly}}=17.0$ to 25.5% and $NMBE_{\text{hourly}}=3.6$ to 10.0% for indoor air temperature across multiple zones. The accuracy of the calibrated model was also tested by using a new set of input weather data for the subsequent year and comparing the simulated and measured data. This paper demonstrates an effective staged approach for creating calibrated models of old buildings under high uncertainty that can be used to influence large-scale decision making for retrofits focused on improving indoor environment quality and energy performance.

5.2 Introduction

About 97% of the buildings in the EU need to be upgraded to meet the 2050 decarbonisation goals [1]. Non-domestic buildings in Europe account for 25% of the total stock and they have an average energy consumption of 280 kWh/m² (including all end uses), 40% higher when compared to the domestic building stock [2]. New buildings represent less than 1.5% of the total building stock in Europe [3]. Thus, retrofits offer greater opportunities, than building new energy efficient buildings to meet Europe’s emission targets. A large stock of non-domestic buildings was built during the post-war years 1945 to 1985 when building regulations were not stringent and had little focus on energy conservation [4]. New technologies resulted in the acceptance of glass and metal curtain walls and the realisation of machine-made envelopes [5]. The implementation of poor building technology, such as lack of insulation/double-glazing, and high-energy consumption are well-defined characteristics to identify them [6]. The majority of
post-war non-domestic buildings followed an international, modernist and minimal style architecture, which is uniform across many of the non-domestic buildings from that period across the EU [7] with either partially or fully glazed façades.

Educational buildings account for the largest share of the oldest buildings in the European non-domestic building stock (EU-27) and the majority of these were constructed before 1980 [2]. After the energy crises in the 1970’s, the thermal energy efficiency of buildings gained importance in legislations across Europe [6]. A recent focus of EU member states has been to retrofit these existing buildings and improve their energy performance. Most often, due to large floor/envelope area or budget constraints, these buildings are retrofitted in ‘piecemeal’ or ‘single measures’ (e.g. double glazing or thermostatic radiator valves (TRVs)) known as ‘shallow retrofit’ [8] and such interventions are often not supported by detailed investigations and fall short of targets [2]. Building energy models (BEM) are increasingly being used to assess the impact of retrofitting interventions (energy conservation measures/ retrofit measures), which are often not accurate and could lead to wrong decisions [9]. Selection of retrofitting strategies is considered effective with the use of calibrated energy models. However, with old non-domestic buildings (>35 yrs.), it is often challenging to acquire detailed data of the building performance for input to develop accurate energy models [10]. The missing information and lack of measured data lead to uncertainties in creating accurate energy models. Achieving a targeted building energy performance is challenging with these buildings, but of dire need considering the current scenario with low-renovation rates in the EU [6].

A stakeholder study [11] highlighted major gaps in the use of modelling and analysis tools for retrofits in the Irish construction industry. Reliability issues with retrofit solutions showed that building stakeholders (e.g. facility managers, contractors, architects, BER assessors, etc.) regarded variation in measured and actual building performance data as a technical challenge that needs to be addressed in the industry practices. Therefore, the study presented here builds on these findings to account for the large uncertainties and inform decision making through a reliable modelling and calibration approach.
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5.3 Model development, uncertainty analysis and calibration for retrofits

BEMs help in predicting the potential energy savings in retrofit through analyses of different scenarios. To this purpose a baseline model is created, for which, the results of predicted energy consumption must closely match the actual energy consumption and these models are further developed to identify energy savings for different retrofit measures [12]. Such models require input data from detailed building audits and surveys. The geometrical, thermo-physical and operational characteristics have to be defined for the development of building energy models. Software used for simulation of energy performance, which works on transient relationships of heat transfer [13], include EnergyPlus, DOE-2, e-Quest, ESP-r IDA ICE, IES-VE, TRNSYS. These platforms are very popular in the industry and the selection of particular transient simulation software depends on users experience and application criteria [14], [15]. Lee et al. [16] showed that out of 18 freely accessible energy retrofit toolkits, 9 used EnergyPlus as their simulation engine, 2 used DOE-2 and e-Quest together, with the remaining based on empirical data driven and normative methods. EnergyPlus has been utilised for several energy retrofit studies of educational buildings, where the investigation aimed at reliable modelling combined with multi-objective optimisation to determine energy conservation measures for achieving low and near zero-energy standards [17]–[19]. It is a robust and well recommended tool within the research community and it is capable of handling complexities in the model due to the possibility of detailed inputs required [20]–[22]. In this work, EnergyPlus is used as the main simulation tool due to its flexible integration with other third-party applications.

Existing non-domestic buildings have large uncertainties involved in the simulation input parameters and, therefore, require uncertainty analysis such as sensitivity analysis [23]. There are certain basic factors that contribute to uncertainty in BEM predictions, such as (i) occupant behaviour, (ii) outdoor weather conditions, (iii) changes due to operation and maintenance, (iv) alterations in indoor environmental conditions, (v) internal heat gains and (vi) building equipment [24]. Due to uncertainty in the input parameters, these models require further tuning of parameters, known as calibration, for achieving a good match with actual performance of the existing building. Often the largest discrepancies occur from the occupant behaviour; therefore, in retrofits, detailed schedules must be developed to reduce the uncertainty [25]. To improve the validity of results from BEM simulations, calibration is conducted. However, currently, there are no standard frameworks to address uncertainty in BEM [26]. A range of
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sources of uncertainty was determined by Heo et al. [27] when carrying out energy retrofit analysis on buildings. The relevance of calibrated models in the retrofit analysis is also highlighted in research for decision making [28].

Sensitivity analysis is often a pre-requisite to the calibration process and is used to minimise the uncertainty [29]. It determines the contribution of the individual simulation parameters to the total energy performance of the BEM. It has been used to find the parameters that account for most of the building performance variance and a pre-requisite to perform calibration on the BEM [30], [31]. Sensitivity analysis methods are classified into local methods (computationally fast with reduced shape and space for input parameters around a base case) and global methods (regression, screen, variance-based and meta-models that examine the influence of uncertain parameters over a whole parameter range) [32]. The choice of methods depends on several factors such as time, cost, research purpose, familiarity with methods and number of input variables. Local sensitivity analysis has been used previously in research with BEMs, to provide building designers an overview of impact by adjusting a focus parameter on indoor environment and energy performance prior to building construction [33]. Global sensitivity analysis methods are popularly known as screening based methods that identify the least important inputs in the building energy simulation that can be fixed to a value without significantly affecting the output from the model [34]. A widely adopted global screening method used for sensitivity analysis in building simulation is the Morris method, as it provides a qualitative measure of the effect of each parameter on model outputs [35]. An application of the Morris method was explored for parameter screening before model calibration for large-scale analysis for building retrofit [36].

In sensitivity analysis, a large parameter set must be identified and undergo screening before calibration. Example software that has been recommended by researchers for sensitivity analyses in building performance analysis include SimLab and R [32].

Calibration is a ‘manual, iterative and pragmatic intervention’ to BEM [39]. Calibration can be based on special tests and analytical methods/procedures. BEM calibration is also referred to as an over parameterised process that has immense interdependencies with input variables representing the complexity of building systems [24]. Generally, in building energy modelling, calibration is done by comparing measured/metered data with simulated data and achieving the acceptance criteria outlined by ASHRAE Guide 14 [37] and IMPVP [38]. A review of several studies has highlighted different methods of calibration of BEMs [9]. Graphical techniques can be used to calibrate models by visualisation of results between simulated and actual data [40].
Manual calibration approaches often work with a limited number of parameters, and are highly time consuming as compared to automated approaches (optimisation techniques and alternative modelling techniques) requiring advanced knowledge of building simulation [41]. Several optimisation approaches are being used by researchers to automate the calibration process such as genetic algorithm (GA), particle-swarm optimisation (PSO) and Bayesian optimisation (BO) [31], [36], [42], [43]. Among GA, NSGA-II has proven its capabilities in optimisation using a natural selection method and has been a popular choice of researchers for single or multi-objective functions [44]–[46]. It works by maintaining a population of individuals and selection of the fittest to move on to the next generations. The diversity of individuals is maintained by crossover and mutation. The NSGA-II works on a non-dominated sorting and ranking process of individuals maintaining the spread of solutions and converges into a non-dominated front [44]. Crowding distance is calculated for each solution to maintain the spread along the front. Most of the BEM tools do not provide native retrofit optimisation. Therefore, third-party optimisation applications are generally used for calibration automation purposes [47].

Model calibration is completed by validating the simulation results with the standard acceptance criteria [38]. The energy model is calibrated based on the resultant parameters obtained from the sensitivity analysis. The parameters are adjusted during the iterative/automated process of calibration. The model is considered calibrated when the acceptable criteria have been met. The acceptable tolerances as per ASHRAE Guideline 14 [37] and IMPVP [38] are given in Table 5.1.

<table>
<thead>
<tr>
<th>Calibration type</th>
<th>Index</th>
<th>ASHRAE Guide 14(^1)</th>
<th>IMPVP(^1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monthly</td>
<td>NMBEMonthly</td>
<td>5%</td>
<td>20%</td>
</tr>
<tr>
<td></td>
<td>CV(RMSE) Monthly</td>
<td>15%</td>
<td>-</td>
</tr>
<tr>
<td>Hourly</td>
<td>NMBEHourly</td>
<td>10%</td>
<td>5%</td>
</tr>
<tr>
<td></td>
<td>CV(RMSE) Hourly</td>
<td>30%</td>
<td>20%</td>
</tr>
</tbody>
</table>

\(^1\)Lower values indicate better calibration; Acronyms: NMBE: normalised mean bias error, CV(RMSE): Coefficient of variation of the root mean squared error

The level of calibration is dependent on the availability of the data and all models should be calibrated using at least monthly data, but ideally more frequent data [37]. A range of data for calibration can be obtained from the actual building, from physical surveys, interviews, building audits, building energy management systems, and other measurements. Therefore, it
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is important to classify the levels of calibration based on the available data [9]. Different levels of calibration are proposed in literature according to the building information available [29], [48], [49]. Level 1 is the basic calibration level without any details of building operation. Level 2 approach requires site verification using as-built data. Level 3 is based on detailed audit and spot measurements. Level 4 and 5 are the most detailed calibration levels where data is collected using data loggers with Level 5 requiring long-term monitoring. The stages of calibration can be determined by combining the different levels of building data available depending on the complexity and details for which the calibration is conducted.

After reviewing several studies, Coakley et al. [41] indicated that empirical model calibration methods can reduce the gap between the actual and simulated data patterns and improve calibration feasibility. One of the most significant parameters that could affect the prediction of energy consumption in BEM is the accuracy of occupancy data and plug loads [50]. These parameters should be first adjusted based on measured data in model calibration, which is generally opposite to the traditional method described in the standards to start calibration with energy utility bills or data [29].

The main objective of this study is to present a methodology for the calibration of an energy model combined with uncertainty analysis of a partially retrofitted non-domestic building (>35 yrs. old), which can subsequently be used to investigate further retrofit opportunities and achieve energy savings. There is a lot of research on building energy model calibration [16]; yet it is not effectively developed for the purpose of retrofit application of old non-domestic buildings and the same is presented in this research. A field study from previous research on indoor environmental quality (IEQ) by the authors [51] is used as a case study to focus on the use of calibrated models for IEQ studies. A brief description of the case study is followed by initial building energy modelling and results. The calibration is carried out using the reference data from the case study and the model is further validated using weather data for the subsequent year.

5.4 Methodology and case study

5.4.1 Method

The main objective of this study is to present an automated optimisation-based calibration methodology that can be utilised by researchers and professionals to calibrate building energy
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models for retrofit of old non-domestic buildings. The calibration methodology is developed based on the available literature and advancements in calibration [49] and considering the requirement of reduced computation time, effort and expertise, making it more robust for general users. The methodology is divided into four main parts as shown in Figure 5.1: (a) model preparation, (b) sensitivity analysis, (c) staged automated calibration and validation, and (d) additional validation.

![Figure 5.1 Calibration methodology](image)

As in Figure 5.1(a), the calibration methodology begins with the development of an initial building energy model (BEM) using building information from audits, construction specifications and technical surveys, together with measured weather data. The environment of OpenStudio®2.4.0 [52] coupled with EnergyPlus® 8.8.0 [21] is used in the BEM.

Prior to calibration, a sensitivity analysis is conducted on the parameters identified most influential on energy consumption based on literature [53]–[55]. The initial model is used to determine the sensitive input parameters using Morris method with SimLab®4.0 [56] and jEPlus®v1.7 [57], as shown in Figure 5.1(b). An automated approach for calibration using NSGA-II optimisation (jEPlus+EA®v1.7.6 coupled with EnergyPlus®8.8.0) is shown in Figure 5.1(c). As discussed in Section 5.3, calibration in this study consolidates the levels of input information divided into two-stages to outline the impact of different measured datasets (utility and temperature) on calibration accuracies [58]. The parameters determined through the
sensitivity analysis were ranked and used for tuning the model during calibration with defined lower and upper bounds. In the first-stage, the model corresponds to Level 1-4, where the optimisation objective functions were set to minimisation of \( \text{Cv(RMSE)}_{\text{Monthly}} \) and \( \text{NMBE}_{\text{Monthly}} \) between measured and simulated data for both heating and electrical monthly energy consumption. The model values were altered automatically based on value constraints during optimisation. The actual monthly utility data of the case study building was available for two years. The first year of data was used in the first-stage, as per the standard practice of energy model calibration to assess the energy performance [37]. Smaller interval (hourly) utility data can also be used in the first-stage for achieving better accuracy. However, utilising detailed measured utility data may not ensure accurate predictions of the indoor environment variables; therefore, predicted indoor temperature from the model was compared to measured data [59]. If the error does not meet the acceptance criteria, further stages may be used for tuning the model to reduce the differences in measured and simulated data indoor environment variables, while minimising the error for energy consumption.

In the second-stage, the model represents Level 1-5, where the optimisation objective functions were set to minimisation of \( \text{Cv(RMSE)}_{\text{Hourly}} \) and \( \text{NMBE}_{\text{Hourly}} \) between measured and simulated hourly indoor air temperature data of each zone with constraints set on indices for heating and electrical energy consumption to be within the threshold values. Using a multi-staged approach can be useful for controlled calibration using multiple datasets.

If the acceptance criteria are not met in the first stage, then the user updates the model until the criteria are met for the first variable (e.g. energy consumption). Once the acceptance criteria are met for the initial variable then the user employs a second (or multiple additional) measured data sets (e.g. air temperature, CO\(_2\), humidity) in the subsequent stage to achieve the acceptance criteria for other variables (e.g. air temperature, CO\(_2\), humidity) based on the purpose of calibration. The corresponding indices \( \text{Cv(RMSE)} \) [%] and \( \text{NMBE} \) [%] for both stages were calculated as per ASHRAE Guideline 14 [37] to achieve the acceptance criteria for calibration in two-stages. An additional validation was conducted using an independent set of measured and weather data, as outlined in Figure 5.1(d). The hardware of the CPU used in the analysis of this research had the following configuration- Intel\textsuperscript{®}Xeon\textsuperscript{®}X5690 @ 3.47 GHz, RAM, 24.0 GB.
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5.4.2 Case study description

The case study building is an education building with a total area of 1073m² located in the campus of the National University of Ireland, Galway in Ireland and housing an academic department. It is connected to the main building from the South-East end and located beside a river on the North-East. The building was built during the 1970s and was partially retrofitted in 2005. There are two floors of the building with 2.71m high false-ceiling and a plenum space of 0.69m (ground floor) and 1.41m (first floor). It comprises of single occupant offices, post-graduate students’ rooms, conference rooms, laboratories and lecture rooms. There are 25 occupied zones in the building (Figure 5.2). A detailed field study of the building conducted previously [51] highlighted the conditions of the building with respect to IEQ and requirements to retrofit the building. Along with the IEQ surveys, detailed surveys and interviews were also conducted as a part of the building energy audit for occupancy, lighting, equipment and energy use. The monitoring period for that study was from June 2016 to May 2017.

5.4.2.1 Building energy audit

The building is occupied throughout the year with weekends generally non-working, but the lecture rooms are only occupied in accordance with the teaching semester schedule (including summer/ winter break and holidays) that was provided by the Building and Estates Office in the university. The facility management department in the Buildings and Estates office also provided individual room booking data for conference rooms and laboratories. All other occupancy schedules were determined through questionnaires with the occupants for single offices and post-graduate students’ rooms.

The building is primarily heated by baseboard heating units fitted with thermostatic radiator valves (TRVs) in every room. The hot water for heating is supplied through a central district heating system with integrated combined heat and power (CHP) unit. The flow temperature is user-adjustable, and supply is controlled by a variable speed pump managed by the facility manager based on the weather conditions. A schedule of flow temperatures was available from the built-in data loggers. There were no individual automatic room thermostats. Due to the absence of room thermostats, there was high uncertainty in the usage of TRVs and their schedules were prepared based on the information from occupants. Both the ground and first floor zones had different valves to control the heating supply. The heating schedule for the building was determined based on the operation schedule of the central district heating system.
adjusted by the facility manager. There was a lack of local controls leading to heating of the building when not required. The heating schedule provided by the Buildings and Estates Office is shown in Table 5.2.

<table>
<thead>
<tr>
<th>Ventilation type</th>
<th>NV</th>
<th>NV &amp; H</th>
<th>NV &amp; H</th>
<th>NV &amp; H</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heating period</td>
<td>--</td>
<td>15/10/16-31/11/16</td>
<td>1/12/16-28/02/17*</td>
<td>1/03/17-14/05/17</td>
</tr>
<tr>
<td>Daily heating schedule</td>
<td>--</td>
<td>Mon-Sat</td>
<td>Sun</td>
<td>Mon-Sat</td>
</tr>
<tr>
<td></td>
<td></td>
<td>08:00-</td>
<td>08:00-</td>
<td>08:00-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>22:00</td>
<td>13:00</td>
<td>22:00</td>
</tr>
</tbody>
</table>

Note: NV= Natural Ventilation; H= Heating; *Heating is turned off for the Christmas vacation period (23/12/16-2/01/17)

The building is naturally ventilated throughout the year and there is no mechanical ventilation present in the building. The building envelope is composed of a single-glazing system (without thermal breaks) and double-glazing system (with thermal breaks) fitted with operable windows in the original and retrofitted façade, respectively (Figure 5.2 and 5.3). The tilted windows in the glazing system are operated by occupants for natural ventilation. The natural ventilation rate is based on previous IEQ research [51]. Blower door tests were conducted in the building to determine the infiltration rate of 2.3 ACH and 3.0 ACH for retrofitted and non-retrofitted zones, respectively.

Other than natural light through the windows, the main source of lighting is artificial lighting with recessed luminaries T8 (parabolic louver and non-vented) with 0.30% of the convective fraction. In all the rooms, daylight and glare are controlled via indoor vertical blinds when there are sunny days. Lecture rooms, due to their higher depth, receive insufficient daylight through the glazing and, thus, are dependent on artificial light throughout the day. The lighting in lecture rooms is fitted with occupancy control which is located above the entrance. The lighting loads were calculated individually for all the zones and the lighting schedules were prepared based on occupants’ survey and interviews.
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Figure 5.2 Floor plans of the case study building [51]

Figure 5.3 Panoramic view of the building

Equipment loads were measured and calculated individually using a watt-meter for each zone based on the equipment present, and their operation schedules were prepared from the information collected in interviews. Convective fractions for equipment were calculated for individual equipment based on literature [60]–[62]. Uncertainty can be attributed to the use of equipment and lighting by the occupants and the schedules cannot represent the exact usage for every hour in the schedule, but overall may represent a good match.
In the previous field study, detailed surveys and interviews were conducted to assess the IEQ of the building and perform short and long-term monitoring [51]. Monthly heating and electrical energy metered data were made available through the Buildings and Estates Office for the period of one year (June 2016- May 2017) and were used in the calibration process. Detailed indoor air temperature data were also collected from June 2016 to May 2017 during the IEQ evaluation along with other physical variables. Therefore, the hourly indoor temperature data was also used for calibrating the model in this study. Although the data were collected at 10-minute intervals, it was averaged over hourly duration for the purpose of calibration as the simulation time-step was also hourly.

A local weather station [63] is located on the roof of the case study building (N53° 16’47” W9° 03’37’’) and recorded weather data at one-minute intervals. The recorded parameters included dry bulb air temperature, relative humidity, barometric pressure, total and diffuse solar irradiation, wind speed, wind direction and rainfall. Uncertainty due to weather data in calibration was minimised due to the availability of measured data from the local weather station for the study period instead of using historical datasets. The collected weather data for Galway was used in the building energy model for simulations using values at hourly time-steps.

5.4.2.2 Initial building energy model

The initial BEM of the case study building was created using OpenStudio (GUI for EnergyPlus) as depicted in Figure 5.4. The initial model was prepared based on the building energy audit, design specification, and technical surveys. The detailed input specifications of the building model (25 zones) including the schedules (occupancy, lighting equipment), loads (equipment and lighting) and heating system were as per the building energy audit (Section 5.4.2). Partial-retrofit of the building posed a few challenges in modelling the individual zones having different façade construction (original and retrofitted) and infiltration rates on both the floors.
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The building construction input details used as model inputs are given in Table 5.3 and are reported according to the technical documentation. Infiltration rates used were based on the blower door test [51]. The minimum indoor temperature for natural ventilation to occur was set to 21°C in the model. Temperature set point data were available through interviews with the occupants, but this parameter was highly variable due to occupants’ behaviour and independent adjustments and was based on their experience and best estimates.

Table 5.3 Input parameters of main building components [51]

<table>
<thead>
<tr>
<th>Component</th>
<th>Average U-value (W m²K⁻¹)</th>
<th>Layers (thickness)</th>
<th>Conductivity (W m⁻¹K⁻¹)</th>
<th>Density (kg m⁻³)</th>
<th>Specific heat capacity (J kg⁻¹K⁻¹)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roof</td>
<td>0.54</td>
<td>Roof membrane (9.5 mm)</td>
<td>0.16</td>
<td>1121</td>
<td>1460</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rockwool insulation (88 mm)</td>
<td>0.049</td>
<td>265</td>
<td>836</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Metal Decking (1.5 mm)</td>
<td>45.06</td>
<td>7680</td>
<td>500</td>
<td></td>
</tr>
<tr>
<td>Ceiling</td>
<td>3.14</td>
<td>Mineral fibre board (19 mm)</td>
<td>0.06</td>
<td>368</td>
<td>590</td>
<td>All zones</td>
</tr>
<tr>
<td>Exterior walls</td>
<td>0.26</td>
<td>Metal panel (5 mm)</td>
<td>45.28</td>
<td>7824</td>
<td>500</td>
<td>All zones</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Board insulation (50 mm)</td>
<td>0.03</td>
<td>43</td>
<td>1210</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rockwool insulation (100 mm)</td>
<td>0.049</td>
<td>265</td>
<td>836</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Plasterboard (12.5 mm)</td>
<td>0.16</td>
<td>800</td>
<td>1090</td>
<td></td>
</tr>
<tr>
<td>Interior walls</td>
<td>2.57</td>
<td>Plaster (20 mm)</td>
<td>0.16</td>
<td>600</td>
<td>1000</td>
<td>All zones</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Concrete block (100 mm)</td>
<td>0.72</td>
<td>1920</td>
<td>840</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Plaster (20 mm)</td>
<td>0.16</td>
<td>600</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>Single glazing</td>
<td>5.79</td>
<td>(metal frame with no thermal break)</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>Non-retrofitted zones</td>
</tr>
<tr>
<td>Double glazing</td>
<td>1.89</td>
<td>(metal frame with thermal break)</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>Retrofitted zones</td>
</tr>
<tr>
<td>First floor slab</td>
<td>4.67</td>
<td>Linoleum tile (8 mm)</td>
<td>0.19</td>
<td>1200</td>
<td>1470</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Concrete dense (300 mm)</td>
<td>1.4</td>
<td>2100</td>
<td>840</td>
<td></td>
</tr>
<tr>
<td>Ground floor slab</td>
<td>2.57</td>
<td>Linoleum tile (8 mm)</td>
<td>0.19</td>
<td>1200</td>
<td>1470</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Screed (75 mm)</td>
<td>0.41</td>
<td>1200</td>
<td>840</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>DPC (3 mm)</td>
<td>0.14</td>
<td>1200</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Concrete dense (200 mm)</td>
<td>1.4</td>
<td>2100</td>
<td>840</td>
<td></td>
</tr>
<tr>
<td>Doors</td>
<td>2.97</td>
<td>Wooden panel (25 mm)</td>
<td>0.15</td>
<td>608</td>
<td>1630</td>
<td>All zones</td>
</tr>
<tr>
<td>Shading</td>
<td></td>
<td>Slat (1.5mm)</td>
<td>0.02</td>
<td>-</td>
<td>-</td>
<td>All zones</td>
</tr>
<tr>
<td>(Vertical blinds)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Chapter 5. An energy model calibration methodology and application with sensitivity analysis for a partially-retrofitted university building

Since there was no room thermostat, the temperature set point was based on the range estimated from the TRV setting (e.g. *,1,2,3,4,5) i.e. 20-24°C. The building did not have any external shading device and had only internal blinds that were modelled. Since the neighbouring buildings did not impose any significant mutual shading throughout the year, therefore, were not modelled. Thermal-bridges were also modelled to take into account the impact of conduction through existing building envelope components. A constant temperature boundary condition was applied for each month of the year for the outside surface temperature for all surfaces adjacent to ground in OpenStudio and construction of earth layers was excluded to reduce complexity [64] in the model. The hourly simulations were run for an annual period (2016-17) using the developed model.

A detailed summary of loads and internal gains used in the initial building energy model are given in Table 5.4, together with individual zone information highlighting the retrofitted and non-retrofitted status.

**Table 5.4 Summary of loads and internal gains**

<table>
<thead>
<tr>
<th>Room</th>
<th>Type of room</th>
<th>Glazing &amp; Orientation</th>
<th>Status</th>
<th>Area (m²)</th>
<th>Occupant load (m² person⁻¹)</th>
<th>Lighting load (W m⁻²)</th>
<th>Equipment load (W m⁻²)</th>
<th>Additional equipment (W m⁻²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G.0</td>
<td>Single office</td>
<td>Double (SW)</td>
<td>R</td>
<td>12.59</td>
<td>12.66</td>
<td>11.4</td>
<td>6.2</td>
<td>167.9</td>
</tr>
<tr>
<td>G.1</td>
<td>Single office</td>
<td>Double (SW)</td>
<td>R</td>
<td>12.09</td>
<td>12.05</td>
<td>11.9</td>
<td>6.4</td>
<td>-</td>
</tr>
<tr>
<td>G.2</td>
<td>Single office</td>
<td>Single (SW)</td>
<td>NR</td>
<td>12.18</td>
<td>12.2</td>
<td>11.8</td>
<td>6.4</td>
<td>48.4</td>
</tr>
<tr>
<td>G.3</td>
<td>Conference room</td>
<td>Single (SW)</td>
<td>NR</td>
<td>30.47</td>
<td>2.54</td>
<td>14.2</td>
<td>2.6</td>
<td>10.9</td>
</tr>
<tr>
<td>G.4</td>
<td>Single office</td>
<td>Single (SW)</td>
<td>NR</td>
<td>12.33</td>
<td>12.35</td>
<td>11.7</td>
<td>6.4</td>
<td>48</td>
</tr>
<tr>
<td>G.5</td>
<td>Single office</td>
<td>Single (SW)</td>
<td>NR</td>
<td>12.16</td>
<td>12.2</td>
<td>11.8</td>
<td>6.4</td>
<td>77.1</td>
</tr>
<tr>
<td>G.6</td>
<td>Single office</td>
<td>Single (SW)</td>
<td>NR</td>
<td>12.38</td>
<td>12.35</td>
<td>23.2</td>
<td>6.3</td>
<td>47.7</td>
</tr>
<tr>
<td>G.7</td>
<td>Single office</td>
<td>Double (SW)</td>
<td>R</td>
<td>18.18</td>
<td>18.18</td>
<td>15.8</td>
<td>4.3</td>
<td>118.4</td>
</tr>
<tr>
<td>G.8</td>
<td>Single office</td>
<td>Single (SW)</td>
<td>NR</td>
<td>18.6</td>
<td>18.52</td>
<td>15.5</td>
<td>4.2</td>
<td>115.9</td>
</tr>
<tr>
<td>G.9</td>
<td>Single office</td>
<td>Single (SW)</td>
<td>NR</td>
<td>11.96</td>
<td>11.9</td>
<td>12</td>
<td>6.5</td>
<td>51.5</td>
</tr>
<tr>
<td>G.10</td>
<td>Single office</td>
<td>Single (SW)</td>
<td>NR</td>
<td>12.14</td>
<td>12.2</td>
<td>11.9</td>
<td>6.4</td>
<td>174.9</td>
</tr>
<tr>
<td>G.11</td>
<td>Single office</td>
<td>Single (NW)</td>
<td>NR</td>
<td>18.7</td>
<td>18.87</td>
<td>15.4</td>
<td>1.4</td>
<td>-</td>
</tr>
<tr>
<td>G.12</td>
<td>Single office</td>
<td>Double (NW)</td>
<td>R</td>
<td>27.01</td>
<td>27.78</td>
<td>15.5</td>
<td>2.8</td>
<td>21.2</td>
</tr>
<tr>
<td>G.13</td>
<td>Conference room</td>
<td>Single (NE)</td>
<td>NR</td>
<td>62.66</td>
<td>2.61</td>
<td>13.8</td>
<td>1.3</td>
<td>52.4</td>
</tr>
<tr>
<td>G.14</td>
<td>Open plan office</td>
<td>Double (NE)</td>
<td>R</td>
<td>36.6</td>
<td>4.98</td>
<td>12.4</td>
<td>15.7</td>
<td>63.2</td>
</tr>
</tbody>
</table>
Chapter 5. An energy model calibration methodology and application with sensitivity analysis for a partially-retrofitted university building

<table>
<thead>
<tr>
<th>G.15</th>
<th>Computer lab</th>
<th>Single (NE)</th>
<th>NR</th>
<th>44.72</th>
<th>2.13</th>
<th>14.5</th>
<th>33.1</th>
<th>29.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>G.16</td>
<td>Open plan office</td>
<td>Double (NE)</td>
<td>R</td>
<td>53.35</td>
<td>5.43</td>
<td>15.9</td>
<td>14.4</td>
<td>73.1</td>
</tr>
<tr>
<td>G.17</td>
<td>Single office</td>
<td>Single (NE)</td>
<td>NR</td>
<td>26.82</td>
<td>6.71</td>
<td>16.1</td>
<td>8.7</td>
<td>14.7</td>
</tr>
<tr>
<td>G.18</td>
<td>Single office</td>
<td>Single (NE)</td>
<td>NR</td>
<td>17.99</td>
<td>17.86</td>
<td>12</td>
<td>4.3</td>
<td>32.8</td>
</tr>
</tbody>
</table>

GF Corridor  Corridor  -  -  83.66  -  6.8  -  -
F.1  Lecture room  Double (SW)  R  91.2  1.3  12.6  -  3
F.2  Lecture room  Double (SW)  R  73.97  1.32  15.6  -  3.7
F.3  Lecture room  Double (SW)  R  89.03  1.27  12.9  -  3.1
F.4  Lecture room  Double (SW)  R  88.87  1.27  13   -  3.1
F.5  Lab  Double (NW)  R  85.89  2.15  10.9  1.8  3.2
F.6  Lab  Double (NW)  R  36.89  7.35  10.9  1.1  -
FF Corridor1 Corridor  Double (NE)  R  49.65  -  7.2  -  -
FF Corridor2 Corridor  Double (NE)  R  21.08  -  6.8  -  -

Note: SW- South West, NW- North West, NE- North East, R-Retrofitted, NR-Non- Retrofitted

5.5 Results and discussion

5.5.1 Sensitivity analysis results using Morris method

The Morris method determines which factors may be considered to have effects that are negligible, linear and additive, or non-linear or involved in interactions with other parameters [32], [65]. It is the least computationally expensive compared to other global sensitivity analysis methods. Therefore, it has been used in this research. The Morris method is widely used in building energy analysis and characterises the inputs based on the concept of elementary effects that are the first-order derivatives of the model [65]–[67]. The elementary effects are determined at various sample points. The mean and standard deviation of elementary effects allow sorting of parameters into linear or non-linear categories based on their impact. Prior to calibration, the sensitivity analysis was conducted using SimLab 4.0 [56]. The inputs were pre-processed, and outputs were post-processed in SimLab. The jEPlus [57] environment was used to run the batch simulations using the EnergyPlus engine (Figure 5.1(b)) coupled with SimLab.

The steps taken for sensitivity analysis using the Morris method [54], [68] are described as:

i. Determination of objective and output variables

In the case study energy model, the main objective was focused on determining energy performance; therefore, the output variable of space heating demand (kWh m⁻² yr⁻¹) was defined.
Chapter 5. An energy model calibration methodology and application with sensitivity analysis for a partially-retrofitted university building

The objectives can also be focused on Indoor Environment Quality (IEQ) (PMV/PPD, indoor temperature, CO\textsubscript{2} levels etc.), but only one objective can be taken at a time. The initial model, described in Section 5.4.2, was used for simulations in the sensitivity analysis.

ii. Selection and definition of Probability Density Functions (PDFs)

Each parameter and their typical values for PDFs were defined based on architectural, economic, technical possibilities or limitations of the case study building [66]. These were used as standard PDFs from existing research and literature such as uniform, log-normal and normal distribution. A list of values and ranges for the 51 parameters employed in the sensitivity analysis are given in Table 5.5. A large parameter set took into account the uncertainties due to age and partial-retrofit of the building that implied variations in construction and occupant preferences in different zones and, thus, difficult to generalise parameters for typical zones [51]. These parameters were assumed to have normal distribution due to large parameter ranges and uncertainty [69]. The initial values were derived from data collected through audits, documentation, standards and calculations based on available information as discussed in Section 5.4.2. The set of parameters that were generally considered for the calibration of a BEM included U-values, loads and set points [53], [54]. The mean and standard deviations of different parameters have been defined based on the literature from which the threshold values of parameters (minimum and maximum) were derived [36], [66], [70], [71]. The values of parameters in Table 5.5 were defined within SimLab based on their PDFs and for each parameter, several samples were pre-processed in the next step under the Morris method.

iii. Generation of simulation input parameters using random sampling (factorial sampling)

Based on the PDF of each simulation parameter, random samples [32], [72] of simulation parameters were generated by Morris factorial sampling [65] in SimLab in this study. The procedure was repeated \( r \) (random trajectories) times creating a set of \( r(k+1) \) simulations, where \( k \) is the number of simulation input parameters. In order to reasonably cover for all simulation parameters, a minimum value of \( r=4 \) is recommended in the literature. Therefore, if there are 51 simulation parameters, then the corresponding simulations to calculate the output will be \( 4(51+1) =208 \).

iv. Calculation of output variables

The random samples obtained for each simulation parameter in the previous step were used as inputs for the simulation to calculate the output variable (total heating energy demand). The
output variable was generated for 208 simulations for each sample of simulation input parameters and this was done using jEPlus along with the EnergyPlus engine. In the next step, the outputs were post-processed in SimLab to evaluate the sensitivity of each parameter based on elementary effects.

v. Relative ranking of simulation parameters based on its impact on the output variables

The main purpose of assessing the influence of each simulation parameter was to determine the effects which were i) negligible, ii) linear or additive, and iii) non-linear. The Morris method determines the elementary effect (EE) of a model \( y = y(x_1...x_k) \) with input (simulation) parameters \( x_i \). The elementary effect for the \( i^{th} \) input parameter in a point \( x_i \) is

\[
EE_i(x_1, \ldots, x_k) = \frac{y(x_1, x_2, \ldots, x_{i-1}, x_i + \Delta x_i, x_{i+1}, \ldots, x_k) - y(x_1, \ldots, x_k)}{\Delta_i}
\]

where, \( \Delta_i \) is the pre-defined step for input parameter \( i \).

Several elementary effects \( EE_i \) of each design parameter were calculated based on the generated samples of each design parameter in step three, i.e. the chosen value of \( r \). The model sensitivity to each simulation parameter was evaluated by the mean and the standard deviation of the elementary effects [65].
### Table 5.5 List of parameters for sensitivity analysis

<table>
<thead>
<tr>
<th>Model component</th>
<th>Code</th>
<th>Parameter</th>
<th>Unit</th>
<th>Source of initial value</th>
<th>Initial model value</th>
<th>Min</th>
<th>Max</th>
<th>( \mu' ) (mean)</th>
<th>( \sigma' ) (standard deviation)</th>
<th>Reference for (( \mu' )) and (( \sigma' ))</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>External wall</strong></td>
<td>P1</td>
<td>Conductivity</td>
<td>W m(^{-1}) K(^{-1})</td>
<td>Datasheets from audit</td>
<td>0.049</td>
<td>0.044</td>
<td>0.054</td>
<td>0.049</td>
<td>0.003</td>
<td>[51]</td>
</tr>
<tr>
<td></td>
<td>P2</td>
<td>Thickness</td>
<td>m</td>
<td>Datasheets from audit</td>
<td>0.1</td>
<td>0.09</td>
<td>0.11</td>
<td>0.1</td>
<td>0.01</td>
<td>[51]</td>
</tr>
<tr>
<td></td>
<td>P3</td>
<td>Density</td>
<td>kg m(^{-3})</td>
<td>Datasheets from audit</td>
<td>265</td>
<td>238.5</td>
<td>291.5</td>
<td>265</td>
<td>18.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>P4</td>
<td>Specific heat</td>
<td>J kg(^{-1}) K(^{-1})</td>
<td>Datasheets from audit</td>
<td>836.8</td>
<td>753.1</td>
<td>920.5</td>
<td>836.8</td>
<td>59.2</td>
<td></td>
</tr>
<tr>
<td><strong>Internal wall</strong></td>
<td>P5</td>
<td>Conductivity</td>
<td>W m(^{-1}) K(^{-1})</td>
<td>datasheets from audit</td>
<td>0.72</td>
<td>0.65</td>
<td>0.79</td>
<td>0.72</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td></td>
<td>P6</td>
<td>Density</td>
<td>kg m(^{-3})</td>
<td>datasheets from audit</td>
<td>1920</td>
<td>1728</td>
<td>2112</td>
<td>1920</td>
<td>135.76</td>
<td></td>
</tr>
<tr>
<td></td>
<td>P7</td>
<td>Specific heat</td>
<td>J kg(^{-1}) K(^{-1})</td>
<td>datasheets from audit</td>
<td>840</td>
<td>756</td>
<td>924</td>
<td>840</td>
<td>59.4</td>
<td></td>
</tr>
<tr>
<td><strong>Roof insulation</strong></td>
<td>P8</td>
<td>Conductivity</td>
<td>W m(^{-1}) K(^{-1})</td>
<td>datasheets from audit</td>
<td>0.049</td>
<td>0.044</td>
<td>0.054</td>
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<tr>
<td></td>
<td>P9</td>
<td>Thickness</td>
<td>m</td>
<td>datasheets from audit</td>
<td>0.088</td>
<td>0.079</td>
<td>0.097</td>
<td>0.088</td>
<td>0.01</td>
<td></td>
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<tr>
<td></td>
<td>P10</td>
<td>Density</td>
<td>kg m(^{-3})</td>
<td>datasheets from audit</td>
<td>265</td>
<td>238.5</td>
<td>291.5</td>
<td>265</td>
<td>18.74</td>
<td></td>
</tr>
<tr>
<td></td>
<td>P11</td>
<td>Specific heat</td>
<td>J kg(^{-1}) K(^{-1})</td>
<td>datasheets from audit</td>
<td>836.8</td>
<td>753.1</td>
<td>920.5</td>
<td>836.8</td>
<td>59.17</td>
<td></td>
</tr>
<tr>
<td><strong>Ground temperature</strong></td>
<td>P12</td>
<td>Ground temperature- outside building surface</td>
<td>°C</td>
<td>Calculated based on average zone temperatures</td>
<td>9</td>
<td>8.1</td>
<td>9.9</td>
<td>9</td>
<td>0.64</td>
<td>Estimated [81]</td>
</tr>
<tr>
<td></td>
<td>P13</td>
<td>Air infiltration (Retrofitted zones)</td>
<td>ACH</td>
<td>Measured from blower door test</td>
<td>2.3</td>
<td>0.92</td>
<td>3.68</td>
<td>2.3</td>
<td>0.98</td>
<td>[51]</td>
</tr>
<tr>
<td></td>
<td>P14</td>
<td>Air infiltration (Non-retrofitted zones)</td>
<td>ACH</td>
<td>Calculated from previous IEQ study [67]</td>
<td>3.02</td>
<td>1.96</td>
<td>4.08</td>
<td>3.02</td>
<td>0.75</td>
<td></td>
</tr>
<tr>
<td></td>
<td>P15</td>
<td>Ventilation rate- Single offices</td>
<td>ACH</td>
<td>Calculated from previous IEQ study [67]</td>
<td>2.9</td>
<td>2.03</td>
<td>3.77</td>
<td>2.9</td>
<td>0.62</td>
<td></td>
</tr>
<tr>
<td></td>
<td>P16</td>
<td>Ventilation rate- Post grad room</td>
<td>ACH</td>
<td>Calculated from previous IEQ study [67]</td>
<td>1.6</td>
<td>1.12</td>
<td>2.08</td>
<td>1.6</td>
<td>0.34</td>
<td></td>
</tr>
<tr>
<td></td>
<td>P17</td>
<td>Ventilation rate- Conference room</td>
<td>ACH</td>
<td>Calculated from previous IEQ study [67]</td>
<td>2.1</td>
<td>1.47</td>
<td>2.73</td>
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<td>0.45</td>
<td></td>
</tr>
<tr>
<td></td>
<td>P18</td>
<td>Ventilation rate- Lab</td>
<td>ACH</td>
<td>Calculated from previous IEQ study [67]</td>
<td>2</td>
<td>1.4</td>
<td>2.6</td>
<td>2</td>
<td>0.42</td>
<td></td>
</tr>
<tr>
<td></td>
<td>P19</td>
<td>Ventilation rate- Lecture room</td>
<td>ACH</td>
<td>Calculated from previous IEQ study [67]</td>
<td>4.2</td>
<td>2.94</td>
<td>5.46</td>
<td>4.2</td>
<td>0.89</td>
<td></td>
</tr>
<tr>
<td><strong>Windows</strong></td>
<td>P20</td>
<td>Solar transmittance (SHGC)-double glazing</td>
<td>-</td>
<td>Datasheets from audit</td>
<td>0.761</td>
<td>0.685</td>
<td>0.837</td>
<td>0.761</td>
<td>0.05</td>
<td>[79]</td>
</tr>
<tr>
<td></td>
<td>P21</td>
<td>Solar transmittance (SHGC)-single glazing</td>
<td>-</td>
<td>Datasheets from audit</td>
<td>0.837</td>
<td>0.753</td>
<td>0.921</td>
<td>0.837</td>
<td>0.06</td>
<td></td>
</tr>
<tr>
<td></td>
<td>P22</td>
<td>Visible transmittance-double glazing</td>
<td>-</td>
<td>Datasheets from audit</td>
<td>0.807</td>
<td>0.726</td>
<td>0.888</td>
<td>0.807</td>
<td>0.06</td>
<td></td>
</tr>
<tr>
<td></td>
<td>P23</td>
<td>Visible transmittance-single glazing</td>
<td>-</td>
<td>Datasheets from audit</td>
<td>0.899</td>
<td>0.809</td>
<td>0.989</td>
<td>0.899</td>
<td>0.06</td>
<td></td>
</tr>
<tr>
<td></td>
<td>P24</td>
<td>Double glazing U-value</td>
<td>W m(^{-1}) K(^{-1})</td>
<td>Datasheets from audit</td>
<td>2.72</td>
<td>2.45</td>
<td>2.99</td>
<td>2.72</td>
<td>0.19</td>
<td>[51]</td>
</tr>
<tr>
<td></td>
<td>P25</td>
<td>Single glazing U-value</td>
<td>W m(^{-1}) K(^{-1})</td>
<td>Datasheets from audit</td>
<td>5.78</td>
<td>5.2</td>
<td>6.36</td>
<td>5.78</td>
<td>0.41</td>
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<tr>
<td><strong>Shading</strong></td>
<td>P26</td>
<td>Vertical blinds- conductivity</td>
<td>W m(^{-1}) K(^{-1})</td>
<td>Datasheets from audit</td>
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<td>0.18</td>
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<td>Code</td>
<td>Parameter</td>
<td>Unit</td>
<td>Source of initial value</td>
<td>Initial model value</td>
<td>Min</td>
<td>Max</td>
<td>$\mu$ (mean)</td>
<td>$\sigma$ (standard deviation)</td>
<td>Reference for ($\mu$') and ($\sigma$')</td>
</tr>
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<td>Internal Loads</td>
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<td>P27</td>
<td>Equipment loads- Single office</td>
<td>W m$^{-2}$</td>
<td>Measured and calculated on-site</td>
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<td>P28</td>
<td>Equipment loads- Post grad room</td>
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<td>Equipment loads- Conference</td>
<td>W m$^{-2}$</td>
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<td>48.2</td>
<td>65.21</td>
<td>56.7</td>
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<td>38.53</td>
<td>33.5</td>
<td>3.55</td>
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<td>P31</td>
<td>Equipment loads- Lecture room</td>
<td>W m$^{-2}$</td>
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<td>2.59</td>
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<td>3.05</td>
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<tr>
<td>P32</td>
<td>P32</td>
<td>Lighting Power Density - Single office</td>
<td>W m$^{-2}$</td>
<td></td>
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<td>2.74</td>
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<td>P33</td>
<td>Lighting Power Density - Post grad room</td>
<td>W m$^{-2}$</td>
<td></td>
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<td>10.93</td>
<td>14.79</td>
<td>12.86</td>
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</tr>
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<td>P34</td>
<td>Lighting Power Density - Conference</td>
<td>W m$^{-2}$</td>
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<td>12.59</td>
<td>15.83</td>
<td>14.81</td>
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<td>W m$^{-2}$</td>
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<td>1.2</td>
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<td>P36</td>
<td>Lighting Power Density - Lecture room</td>
<td>W m$^{-2}$</td>
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<td>11.48</td>
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<tr>
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<td>P37</td>
<td>Occupant density- Single office</td>
<td>person m$^{-2}$</td>
<td>Calculated from audit and room booking data</td>
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<td>0.05</td>
<td>0.09</td>
<td>0.07</td>
<td>0.01</td>
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<td>P38</td>
<td>P38</td>
<td>Occupant density- Post grad room</td>
<td>person m$^{-2}$</td>
<td></td>
<td>0.19</td>
<td>0.13</td>
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<td>0.19</td>
<td>0.04</td>
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<td>P39</td>
<td>P39</td>
<td>Occupant density- Conference</td>
<td>person m$^{-2}$</td>
<td></td>
<td>0.39</td>
<td>0.27</td>
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<td>0.39</td>
<td>0.08</td>
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<td>P40</td>
<td>P40</td>
<td>Occupant density- Lab</td>
<td>person m$^{-2}$</td>
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<td>0.3</td>
<td>0.21</td>
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<td>0.3</td>
<td>0.06</td>
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<td>P41</td>
<td>P41</td>
<td>Occupant density- Lecture room</td>
<td>person m$^{-2}$</td>
<td></td>
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<td>0.54</td>
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<td>0.77</td>
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</tr>
<tr>
<td>P42</td>
<td>P42</td>
<td>Indoor Heating setpoint- Single office</td>
<td>°C</td>
<td>EN15251</td>
<td>20</td>
<td>18</td>
<td>22</td>
<td>20</td>
<td>1.41</td>
<td>Estimated</td>
</tr>
<tr>
<td>P43</td>
<td>P43</td>
<td>Indoor Heating setpoint- Post grad room</td>
<td>°C</td>
<td></td>
<td>20</td>
<td>18</td>
<td>22</td>
<td>20</td>
<td>1.41</td>
<td></td>
</tr>
<tr>
<td>P44</td>
<td>P44</td>
<td>Indoor Heating setpoint- Conference room</td>
<td>°C</td>
<td></td>
<td>20</td>
<td>18</td>
<td>22</td>
<td>20</td>
<td>1.41</td>
<td></td>
</tr>
<tr>
<td>P45</td>
<td>P45</td>
<td>Indoor Heating setpoint- Lab</td>
<td>°C</td>
<td></td>
<td>20</td>
<td>18</td>
<td>22</td>
<td>20</td>
<td>1.41</td>
<td></td>
</tr>
<tr>
<td>P46</td>
<td>P46</td>
<td>Indoor Heating setpoint- Lecture room</td>
<td>°C</td>
<td></td>
<td>20</td>
<td>18</td>
<td>22</td>
<td>20</td>
<td>1.41</td>
<td></td>
</tr>
<tr>
<td>P47</td>
<td>P47</td>
<td>Indoor Heating setpoint- Corridor</td>
<td>°C</td>
<td></td>
<td>18</td>
<td>16.2</td>
<td>19.8</td>
<td>18</td>
<td>1.27</td>
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<tr>
<td>P48</td>
<td>P48</td>
<td>Pump efficiency</td>
<td>-</td>
<td>Label data</td>
<td>0.75</td>
<td>0.64</td>
<td>0.86</td>
<td>0.75</td>
<td>0.1</td>
<td>[79]</td>
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<td>Internal gains</td>
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<td></td>
<td></td>
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<tr>
<td>P49</td>
<td>P49</td>
<td>Lighting heat gain radiant fraction</td>
<td>-</td>
<td>ASHRAE Handbook</td>
<td>0.1</td>
<td>0.09</td>
<td>0.12</td>
<td>0.1</td>
<td>0.01</td>
<td>[79]</td>
</tr>
<tr>
<td>P50</td>
<td>P50</td>
<td>Equipment heat gain radiant fraction</td>
<td>-</td>
<td></td>
<td>0.1</td>
<td>0.09</td>
<td>0.12</td>
<td>0.1</td>
<td>0.01</td>
<td>[79]</td>
</tr>
<tr>
<td>P51</td>
<td>P51</td>
<td>Occupant heat gain radiant fraction</td>
<td>-</td>
<td></td>
<td>0.3</td>
<td>0.26</td>
<td>0.35</td>
<td>0.3</td>
<td>0.03</td>
<td>[79]</td>
</tr>
</tbody>
</table>
Chapter 5. An energy model calibration methodology and application with sensitivity analysis for a partially-retrofitted university building

The method of elementary effects was used for this purpose, where each parameter was evaluated using the mean ($\mu$) and standard deviation ($\sigma$) [74]:

$$\mu = \frac{\sum_{i=1}^{r} |EE|}{r}$$  \hspace{1cm} (5.1)

$$\sigma = \sqrt{\frac{\sum_{i=1}^{r} |EE_i - \mu|^2}{r}}$$  \hspace{1cm} (5.2)

where $\mu$ is the mean value of the absolute values of outputs if the simulation parameter is important and $\sigma$ is the standard deviation of the outputs which is a measure of all interactions with other factors.

A resulting elementary effects plot between $\mu$ and $\sigma$, determined through Equations (5.1) and (5.2), is illustrated in Figure 5.5, which shows the linear parameters that are below $\sigma/\mu=0.1$, $0.5>\sigma/\mu>0.1$ (monotonic), $0.1>\sigma/\mu>0.5$ (almost monotonic) and for others that have $\sigma/\mu>1$ are non-monotonic and non-linear [55].

![Figure 5.5 Sensitivity analysis results](image)

Finally, the result of the sensitivity analysis was a list of important simulation parameters and a ranking of the simulation parameters by the strength of their impact on the output $\mu$ (absolute
mean of elementary effect), as shown in Table 5.6. Based on input categorisation in Table 5.5, zone set-points impact (µ) added together (single offices, lecture rooms, laboratories, conference rooms, post-graduate researcher rooms and corridor) and infiltration rates impact (µ) added together (retrofitted and non-retrofitted) contributed to the highest uncertainty in the model results.

Table 5.6 Top 25 ranking parameters after sensitivity analysis

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Rank</th>
<th>Absolute mean of elementary effect (µ) kWh yr⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>P12</td>
<td>1</td>
<td>5630</td>
</tr>
<tr>
<td>P42</td>
<td>2</td>
<td>4800</td>
</tr>
<tr>
<td>P13</td>
<td>3</td>
<td>4140</td>
</tr>
<tr>
<td>P46</td>
<td>4</td>
<td>3750</td>
</tr>
<tr>
<td>P45</td>
<td>5</td>
<td>2760</td>
</tr>
<tr>
<td>P9</td>
<td>6</td>
<td>2460</td>
</tr>
<tr>
<td>P14</td>
<td>7</td>
<td>2270</td>
</tr>
<tr>
<td>P44</td>
<td>8</td>
<td>1660</td>
</tr>
<tr>
<td>P24</td>
<td>9</td>
<td>1400</td>
</tr>
<tr>
<td>P47</td>
<td>10</td>
<td>1380</td>
</tr>
<tr>
<td>P41</td>
<td>11</td>
<td>1330</td>
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<tr>
<td>P8</td>
<td>12</td>
<td>1250</td>
</tr>
<tr>
<td>P20</td>
<td>13</td>
<td>948</td>
</tr>
<tr>
<td>P25</td>
<td>14</td>
<td>789</td>
</tr>
<tr>
<td>P40</td>
<td>15</td>
<td>764</td>
</tr>
<tr>
<td>P43</td>
<td>16</td>
<td>708</td>
</tr>
<tr>
<td>P36</td>
<td>17</td>
<td>639</td>
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<td>624</td>
</tr>
<tr>
<td>P38</td>
<td>19</td>
<td>576</td>
</tr>
<tr>
<td>P39</td>
<td>20</td>
<td>391</td>
</tr>
<tr>
<td>P32</td>
<td>21</td>
<td>386</td>
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<td>323</td>
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<td>312</td>
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<td>P19</td>
<td>24</td>
<td>295</td>
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<tr>
<td>P28</td>
<td>25</td>
<td>291</td>
</tr>
</tbody>
</table>
Chapter 5. An energy model calibration methodology and application with sensitivity analysis for a partially-retrofitted university building

Since outside building surface temperature in touch with ground has lower fluctuations annually, it has lower uncertainty compared to the combined set points and combined infiltration rates of all the zones [69]. However, due to the absence of floor insulation in the BEM, the large impact is visible on $\mu$ owing to large floor surface area in contact with the ground. Among others, double glazing U-value and roof insulation thickness were also influential on the output. It is recommended in literature to limit the calibration parameters to 25 or lower in case of a higher number of optimisation parameters [39]. Therefore, the top 25 parameters were chosen for calibration in the next section.

5.5.2 Model calibration results and additional validation

As outlined in the methodology section, the calibration was divided into two-stages. The first-stage calibration involved the use of the initial building energy model created with as-built components and data as highlighted in Section 5.4.2. The measured monthly utility data of heating and electrical energy consumption was used as reference data for the first-stage calibration. During the second-stage calibration, both the monthly utility data and an extensive set of measured indoor thermal environment data, collected through long-term monitoring of indoor air temperature using data-loggers, were used as reference data. Both stages were validated [75] after calibration against the acceptance criteria in ASHRAE Guideline 14 [37]. The following sections elaborate on the procedures used for calibration and analysis of results obtained from the two stages of calibration.

The calibration in both stages was performed using NSGA-II optimisation. The program jEPlus+EA [57] was used for completing the optimisation on the parameters to achieve the acceptance criteria by validating against the statistical indices. EnergyPlus was used for batch simulations within the interface. A population (number of solutions evaluated in each iteration) of 30 was chosen due to available the CPU (6 cores, 12 threads) and a large number of calibration parameters (25). A higher number of generations improves the accuracy of the solutions [76]; therefore, maximum generations were set to 200 for both the stages. A high value of 1 (100%) was taken for the crossover rate and a lower mutation rate of 0.2 (20%) was employed to avoid randomisation by the algorithm. Convergence was chosen as the stopping criteria of the optimisation algorithm. Convergence stability percentage (based on the mean and standard deviation of outputs) was set to 5% and when the iterations reached the desired level of stability the optimisation converged (population stable with regard to previous one).
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**First-stage calibration**

The top 25 parameters identified in Section 5.5.1 were used for the first-stage calibration process. The initial building energy model used for the sensitivity analysis is employed in the first-stage calibration, during which 26 parameters were maintained at their initial value due to the relatively low impact of varying them on simulation results. The resolution of input data employed in the BEM for model calibration during this stage corresponds to a near accurate representation of the real building conditions, as the information used represents Level 1-4 [48].

The input parameters P42, P43, P44, P45, P46 given in Tables 5.5 and 5.6 were based on the standard EN15251 [77] during this stage of calibration, as measured set-points were not used. Table 5.7 gives the minimum, maximum and step values used for the automated calibration (tuning of parameters). A two-objective optimisation was conducted on the model corresponding to a minimisation of $C_v(\text{RMSE})_{\text{Monthly}}$ and $\text{NMBE}_{\text{Monthly}}$ values for the model based on measured and simulated data of the monthly heating and electrical consumption. During the first-stage calibration, the convergence was achieved after 140 generations as no more optimal solutions were found and the optimisation was terminated. The pareto frontier obtained after convergence is given in Figure 5.6. The ‘knee’ point [78] of the pareto front was selected as the most optimal solution for further stage calibration.

*Table 5.7 Selected top 25 input parameters for first-stage calibration*

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Min</th>
<th>Step</th>
<th>Max</th>
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</thead>
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<td>P12 Ground temperature-outside building</td>
<td>8.1</td>
<td>0.450</td>
<td>9.9</td>
</tr>
<tr>
<td>P42 Indoor Heating Setpoint-Single office</td>
<td>18</td>
<td>1.000</td>
<td>22</td>
</tr>
<tr>
<td>P13 Air infiltration (Retrofitted zones)</td>
<td>0.92</td>
<td>0.690</td>
<td>3.68</td>
</tr>
<tr>
<td>P46 Indoor Heating Setpoint-Lecture room</td>
<td>18</td>
<td>1.000</td>
<td>22</td>
</tr>
<tr>
<td>P45 Indoor Heating Setpoint-Lab</td>
<td>18</td>
<td>1.000</td>
<td>22</td>
</tr>
<tr>
<td>P9 Roof insulation thickness</td>
<td>0.079</td>
<td>0.005</td>
<td>0.097</td>
</tr>
<tr>
<td>P14 Air infiltration (non-retrofitted zones)</td>
<td>1.96</td>
<td>0.530</td>
<td>4.08</td>
</tr>
<tr>
<td>P44 Indoor Heating Setpoint-Conference</td>
<td>18</td>
<td>1.000</td>
<td>22</td>
</tr>
<tr>
<td>P24 Double glazing U-value</td>
<td>2.448</td>
<td>0.136</td>
<td>2.992</td>
</tr>
<tr>
<td>P47 Indoor Heating Setpoint-Corridor</td>
<td>16</td>
<td>1.000</td>
<td>20</td>
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<td>P41 Occupant density-Lecture room</td>
<td>0.54</td>
<td>0.115</td>
<td>1</td>
</tr>
<tr>
<td>P8 Roof insulation conductivity</td>
<td>0.044</td>
<td>0.003</td>
<td>0.054</td>
</tr>
<tr>
<td>P20 Solar transmittance (SHGC)-double glazing</td>
<td>0.685</td>
<td>0.038</td>
<td>0.837</td>
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<tr>
<td>P25 Single glazing U-value</td>
<td>5.2</td>
<td>0.290</td>
<td>6.36</td>
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</table>
Chapter 5. An energy model calibration methodology and application with sensitivity analysis for a partially-retrofitted university building

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>P40</td>
<td>Occupant density- Lab</td>
<td>0.21</td>
<td>0.045</td>
</tr>
<tr>
<td>P43</td>
<td>Indoor Heating Setpoint- Post grad room</td>
<td>18</td>
<td>1.000</td>
</tr>
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<td>P36</td>
<td>Lighting Power density- Lecture room</td>
<td>11.475</td>
<td>1.013</td>
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<td>P27</td>
<td>Equipment loads- Single office</td>
<td>65.96</td>
<td>5.820</td>
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<td>P38</td>
<td>Occupant density- Post-grad room</td>
<td>0.13</td>
<td>0.030</td>
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<tr>
<td>P39</td>
<td>Occupant density- Conference</td>
<td>0.27</td>
<td>0.060</td>
</tr>
<tr>
<td>P32</td>
<td>Lighting Power density- Single office</td>
<td>10.93</td>
<td>0.965</td>
</tr>
<tr>
<td>P21</td>
<td>Solar transmittance (SHGC)-single glazing</td>
<td>0.753</td>
<td>0.042</td>
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<tr>
<td>P33</td>
<td>Lighting Power density- Post grad room</td>
<td>12.59</td>
<td>1.110</td>
</tr>
<tr>
<td>P19</td>
<td>Ventilation rate- Lecture room</td>
<td>2.94</td>
<td>0.630</td>
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<td>P28</td>
<td>Equipment loads- Lecture room</td>
<td>48.2</td>
<td>4.253</td>
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</table>

Figure 5.6 Pareto frontier after first-stage calibration

The first-stage calibration results are shown in Table 5.8 validated against the indices of \( \text{Cv(RMSE)}_{\text{Monthly}} \) and \( \text{NMBE}_{\text{Monthly}} \) for electrical and heating energy consumption nearly satisfying the acceptance criteria of 15% and 5%, respectively (Table 5.1). There were 25 zones in the simulation, but due to space constraints for data presentation only representative zones (G.0, G.1, G.3, G.10, G.12, F.1, F.4, F.6) are used for discussion of results.
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Table 5.8 First-stage calibration results

<table>
<thead>
<tr>
<th></th>
<th>Cv(RMSE)Monthly [%]</th>
<th>NMBEMonthly [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Electricity</td>
<td>15.5</td>
<td>0.1</td>
</tr>
<tr>
<td>Heating energy</td>
<td>9.8</td>
<td>4.7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Indoor air temperature</th>
<th>Cv(RMSE)Hourly [%]</th>
<th>NMBEHourly [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Office (G.0)</td>
<td>25.5</td>
<td>16.2</td>
</tr>
<tr>
<td>Single Office (G.1)</td>
<td>26.7</td>
<td>8.9</td>
</tr>
<tr>
<td>Conference Room (G.3)</td>
<td>28.4</td>
<td>14.7</td>
</tr>
<tr>
<td>Single Office (G.10)</td>
<td>23.4</td>
<td>7.7</td>
</tr>
<tr>
<td>Single Office (G.12)</td>
<td>27.3</td>
<td>12.7</td>
</tr>
<tr>
<td>Open plan office (G.14)</td>
<td>27.0</td>
<td>12.8</td>
</tr>
<tr>
<td>Lecture room (F.1)</td>
<td>24.3</td>
<td>15.4</td>
</tr>
<tr>
<td>Lecture room (F.4)</td>
<td>29.8</td>
<td>15.7</td>
</tr>
<tr>
<td>Lab (F.6)</td>
<td>28.6</td>
<td>14.8</td>
</tr>
</tbody>
</table>

The model results obtained during first-stage calibration were also separately checked for the hourly indices of indoor air temperature to validate the model and it was observed that Cv(RMSE)Hourly were lower than 30% for all the representative zones, but failed the criteria for NMBEHourly as most of the values exceeded 10% criteria. Therefore, second-stage calibration was required to satisfy the acceptance criteria using high resolution reference data and improve the accuracy of the model. These results were associated with the period of June 2016- May 2017.

Second-stage calibration

The first-stage calibration model was used in the second-stage calibration. In other words, all the input parameters were set as those obtained at the end of the first stage calibration. The same steps defined in Table 5.7 were used for each parameter, except the indoor heating setpoint ranges were based on measured indoor temperature data in this stage. During this stage detailed indoor monitoring temperature was available; therefore, it was used in setpoint schedules. The second-stage calibration began by defining the objectives of minimising Cv(RMSE) and NMBE for hourly indoor temperature data and setting the constraint boundaries for monthly heating and electrical energy consumption within the acceptance criteria defined in Section 5.2. For this stage, the hourly indoor air temperature was obtained.
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by averaging measured 10-minute interval data for each hour for the duration of June 2016 to May 2017 due to simulation time-step used. The Pareto frontier was obtained after convergence for the optimisation objectives after 140 generations as presented in Figure 5.7. The non-dominated best solutions are represented by red dots plotted between the sum of Cv(RMSE) and the sum of NMBE for all the zones. The ‘knee’ point was selected as the best solution for this stage.

![Figure 5.7 Pareto frontier for the second-stage calibration](image)

Table 5.9 presents the results of monthly and hourly calibration results where both were validated against the acceptance criteria. Cv(RMSE)\_Monthly and NMBE\_Monthly values were below 15% and 5%, respectively, for heating and electrical energy consumption. Although Cv(RMSE)\_Hourly was below 30%, high NMBE\_Hourly values of indoor air temperature, except for few zones, indicated the presence of uncertainty in parameters and its impact on the output. Results analysis indicated that there was an improvement in the criteria for hourly indoor air temperature compared to the first-stage, where set points were taken based on EN15251 [77]. However, during the second-stage calibration, the set points were automatically tuned during optimisation to best represent the actual temperature data. An improvement in the calibration criteria of Cv(RMSE) for heating and electrical energy consumption was observed in Table 5.9 compared to first-stage results.
Table 5.9 Second-stage calibration results

<table>
<thead>
<tr>
<th></th>
<th>CV(RMSE)_Monthly [%]</th>
<th>NMBE_Monthly [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Electricity</td>
<td>14.4</td>
<td>2.5</td>
</tr>
<tr>
<td>heating consumption</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Heating</td>
<td>9.0</td>
<td>4.6</td>
</tr>
<tr>
<td>consumption</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Indoor air temperature</th>
<th>CV(RMSE)_Hourly [%]</th>
<th>NMBE_Hourly [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Office (G.0)</td>
<td>19.2</td>
<td>8.3</td>
</tr>
<tr>
<td>Single Office (G.1)</td>
<td>23.5</td>
<td>3.6</td>
</tr>
<tr>
<td>Conference Room (G.3)</td>
<td>25.3</td>
<td>10.0</td>
</tr>
<tr>
<td>Single Office (G.10)</td>
<td>22.0</td>
<td>2.9</td>
</tr>
<tr>
<td>Single Office (G.12)</td>
<td>25.2</td>
<td>7.3</td>
</tr>
<tr>
<td>Open plan office (G.14)</td>
<td>25.5</td>
<td>9.8</td>
</tr>
<tr>
<td>Lecture room (F.1)</td>
<td>17.0</td>
<td>6.7</td>
</tr>
<tr>
<td>Lecture room (F.4)</td>
<td>25.6</td>
<td>9.1</td>
</tr>
<tr>
<td>Lab (F.6)</td>
<td>23.9</td>
<td>10.0</td>
</tr>
</tbody>
</table>

Similar accuracies were also obtained in the other zones of the building for indoor air temperature data. However, high CV(RMSE) and NMBE values depicted the presence of uncertainties in modelling the partially-retrofitted building to match the actual operational conditions. A comparison of monthly heating and electrical energy consumption for the measured data and simulation results from the two stages of calibration is shown in Figure 5.8 and Figure 5.9 corresponding to the duration of 2016-17. The monthly energy consumption results do not indicate major improvement, rather slight increase due to adjustment of indoor air temperature setpoint parameter values against reference datasets.
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Figure 5.8 Monthly heating energy consumption comparison

Figure 5.9 Monthly electrical energy comparison

The final set of 51 (25 calibrated plus 26 uncalibrated) parameter values after second-stage calibration are given in Table 5.10 representing the BEM and the near real conditions of the building for the simulation period. The results of second-stage calibration highlighted that P13 attained a lower value compared to P14 depicting that retrofitted zones had lower infiltration rates than non-retrofitted zones. This is also confirmed by a previous study [51]. Measured room temperatures datasets during second-stage calibration converged the infiltration rate values to match the existing scenario of retrofitted and non-retrofitted rooms.

Table 5.10 Final set of model parameter values obtained after the model calibration

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>W m⁻¹ K⁻¹</td>
<td>0.049</td>
<td>P27</td>
<td>W m⁻²</td>
<td>95.93</td>
</tr>
<tr>
<td>P2</td>
<td>m</td>
<td>0.1</td>
<td>P28</td>
<td>W m⁻²</td>
<td>65.21</td>
</tr>
<tr>
<td>P3</td>
<td>kg m⁻³</td>
<td>265</td>
<td>P29</td>
<td>W m⁻²</td>
<td>33.5</td>
</tr>
<tr>
<td>P4</td>
<td>J kg⁻¹ K⁻¹</td>
<td>836.8</td>
<td>P30</td>
<td>W m⁻²</td>
<td>3.05</td>
</tr>
<tr>
<td>P5</td>
<td>W m⁻¹ K⁻¹</td>
<td>0.72</td>
<td>P31</td>
<td>W m⁻²</td>
<td>3.22</td>
</tr>
<tr>
<td>P6</td>
<td>kg m⁻³</td>
<td>1920</td>
<td>P32</td>
<td>W m⁻²</td>
<td>14.79</td>
</tr>
<tr>
<td>P7</td>
<td>J kg⁻¹ K⁻¹</td>
<td>840</td>
<td>P33</td>
<td>W m⁻²</td>
<td>17.1</td>
</tr>
<tr>
<td>P8</td>
<td>W m⁻¹ K⁻¹</td>
<td>0.046</td>
<td>P34</td>
<td>W m⁻²</td>
<td>14</td>
</tr>
<tr>
<td>P9</td>
<td>m</td>
<td>0.087</td>
<td>P35</td>
<td>W m⁻²</td>
<td>11.3</td>
</tr>
<tr>
<td>P10</td>
<td>kg m⁻³</td>
<td>265</td>
<td>P36</td>
<td>W m⁻²</td>
<td>12.47</td>
</tr>
<tr>
<td>P11</td>
<td>J kg⁻¹ K⁻¹</td>
<td>836.8</td>
<td>P37</td>
<td>person m⁻²</td>
<td>0.07</td>
</tr>
<tr>
<td>P12</td>
<td>°C</td>
<td>8.91</td>
<td>P38</td>
<td>person m⁻²</td>
<td>0.17</td>
</tr>
</tbody>
</table>
Comparisons of averaged daily indoor air temperature data between the measured and simulated data from the first and second-stage calibration results for representative zones are shown in Figure 5.10 (a-h). The simulated individual zone temporal annual temperature profiles match the trends and satisfied the required calibration criteria. However, these figures highlight the under-estimation by the model of indoor air temperature values due to uncertainties in the model inputs that may correspond to inaccuracies in physical properties of the building, rates of infiltration or ventilation, schedules and manual operation of thermostats (set points/setback), among others. The calibrated model shows under prediction of daily average temperatures during the summer (June-August), winter (Dec-Feb), spring (Mar-May) and autumn (Sep-Nov) season. However, from mid-October to early-May the model prediction is better as the heating is operational and temperature fluctuations match the setpoint settings. Apart from this duration the building is naturally ventilated, therefore, the model predictions vary with greater deviations for indoor air temperature showing inability of the model to apply ventilation rate accurately. To identify the seasonal accuracy of the model, root mean square deviation (RMSD) between daily averaged measured and simulated II data were calculated for the single office G.0. Better accuracy was observed in the model results for winter (RMSD=2.23) and autumn (RMSD=2.28), followed by summer (RMSD=2.58) and spring (RMSD=2.86).
Figure 5.10 Daily averaged room temperature plot for measured and simulated hourly data
Chapter 5. An energy model calibration methodology and application with sensitivity analysis for a partially-retrofitted university building

In Figure 5.11, an example of a weekly comparison of hourly simulated and measured data for the four seasons is given for one room, ‘Single office G.0’. The criteria for $Cv(RMSE)_{\text{Hourly}}$ and $NMBE_{\text{Hourly}}$ values of 30% and 10% are satisfied with these resultant profiles. However, a major finding from these results emerges that with such old non-domestic building (>35 yrs.), it is difficult to achieve higher calibration accuracies at hourly levels with regard to the indoor thermal environment.

![Image of Figure 5.11: Weekly comparison of hourly measured and simulated data (e.g. Single office G.0)](image)

Additional validation

The model in the previous section was calibrated and validated against standard acceptance criteria in ASHRAE Guideline 14 [37] from June 2016 - May 2017. Therefore, to further ensure the accuracy of the calibrated model, an additional validation was conducted by comparing the energy consumption and indoor temperature data that was measured in the actual building for a subsequent year (May 2017 - April 2018) against that predicted by the model. Previous research has also highlighted that a major source of uncertainty in calibrated model results is weather dataset, which can have inaccuracies and discrepancies [79]; therefore, the weather data set was updated using measured data from the NUI Galway local weather station from May 2017 to April 2018 [63]. All other input parameters in the model remained unchanged, assuming that the semester schedules were similar to the previous year.
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The results of validation are presented in Table 5.11, where $Cv(RMSE)_{\text{Monthly}}$ for electricity consumption is 15.1%, nearly satisfying the criteria, and for heating energy consumption it is 14.3% as compared to 9.0% in second-stage results. $Cv(RMSE)_{\text{Hourly}}$ and $\text{NMBE}_{\text{Hourly}}$ for indoor air temperature of all the representative zones also met the acceptance criteria indicating good calibration accuracy of the model compared to the second-stage results.

![Table 5.11 Validation results against utility and temperature data of 2017-18](image)

<table>
<thead>
<tr>
<th></th>
<th>$Cv(RMSE)_{\text{Monthly}}$ [%]</th>
<th>$\text{NMBE}_{\text{Monthly}}$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Electricity consumption</td>
<td>15.1</td>
<td>3.5</td>
</tr>
<tr>
<td>Heating energy consumption</td>
<td>14.3</td>
<td>0.9</td>
</tr>
<tr>
<td>Indoor air temperature</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single Office (G.0)</td>
<td>20.3</td>
<td>7.6</td>
</tr>
<tr>
<td>Single Office (G.1)</td>
<td>23.1</td>
<td>3.1</td>
</tr>
<tr>
<td>Conference Room (G.3)</td>
<td>24.6</td>
<td>9.9</td>
</tr>
<tr>
<td>Single Office (G.10)</td>
<td>23.8</td>
<td>5.6</td>
</tr>
<tr>
<td>Single Office (G.12)</td>
<td>26.7</td>
<td>4.8</td>
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<tr>
<td>Open plan office (G.14)</td>
<td>24.1</td>
<td>10.0</td>
</tr>
<tr>
<td>Lecture room (F.1)</td>
<td>18.2</td>
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<td>Lecture room (F.4)</td>
<td>24.2</td>
<td>6.1</td>
</tr>
<tr>
<td>Lab (F.6)</td>
<td>25.1</td>
<td>9.7</td>
</tr>
</tbody>
</table>

5.6 Conclusions and future work

In this study, the techniques for automated calibration involved the use of simulation tools, uncertainty analysis and optimisation using genetic algorithm (NSGA-II) for developing BEM to be used for retrofitting applications. The purpose of this research was to present a novel and integrated calibration methodology that could be utilised for producing reliable calibrated models of old non-domestic buildings (>35 yrs.) with limited measured data and high uncertainty. A greater impact on energy consumption and indoor temperature could be attributed to the occupant interaction with thermostats on the radiators, infiltration rates, occupant density and building physical properties based on the sensitivity analysis results. Therefore, it is important to conduct detailed assessment of existing buildings prior to model development and calibration. The main conclusions of the research conducted are:
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i. No standard protocols are available to develop calibrated models for existing non-domestic buildings; therefore, this research presented an approach to address this gap.

ii. The use of automated multi-stage calibration was preferred over manual iterative calibration, as it enabled the alteration of more than one parameter simultaneously and optimise among 25 parameter value constraint sets.

iii. The Morris method enabled the sensitivity analysis of a large parameter set (51) with reduced computation time making it suitable for use with high number of parameters.

iv. The methodology explored the complete process required to carry out the calibration process in stages for an existing building with reduced coding inputs and by coupling the simulation tools.

v. It is important that (i) monthly energy consumption data is available for the initial stages of calibration and (ii) hourly indoor environment data can be used for detailed calibration, to achieve better model accuracy.

vi. The developed calibration methodology provides an approach for the development of models to be used for the different IEQ (e.g. thermal comfort and indoor air quality) studies along with energy consumption.

vii. The results indicated that it is difficult to achieve higher calibration accuracies for indoor temperatures of buildings with a large number of zones.

viii. The model data incorporates information from an occupied building; therefore, this approach is applicable to existing occupied buildings.

ix. Additional validation of the model for a subsequent year by only updating the weather dataset to that measured and independent measured data proved the accuracy of the calibrated model.

This study was an initial step in calibrating the building energy model of an old non-domestic building with uncertainties using monthly utility and hourly indoor temperature data. It also highlighted the performance of partial-retrofit and its impact through sensitivity analysis. Making decisions on potential retrofit solutions based on non-calibrated models may lead to uncertainties, and potentially significant inaccuracies, in the thermal and energy performance of the existing buildings. Future research will be done to quantify the effects of retrofit decision-making using the calibrated building energy model on the indoor comfort parameters, energy efficiency and life-cycle costs of the building. Another sampling method can be employed during uncertainty analysis for improving the accuracy of the results. Higher
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Frequency data is preferred for energy consumption that could provide improved accuracy in the first-stage calibration. The methodology may also be tested on buildings with higher complexity in heating, ventilation and air conditioning (HVAC) systems.

5.7 References


Chapter 5. An energy model calibration methodology and application with sensitivity analysis for a partially-retrofitted university building


Chapter 5. An energy model calibration methodology and application with sensitivity analysis for a partially-retrofitted university building

2016.


Chapter 5. An energy model calibration methodology and application with sensitivity analysis for a partially-retrofitted university building


Chapter 5. An energy model calibration methodology and application with sensitivity analysis for a partially-retrofitted university building


Chapter 5. An energy model calibration methodology and application with sensitivity analysis for a partially-retrofitted university building


[74] F. Campolongo, A. Saltelli, and J. Cariboni, “From screening to quantitative sensitivity
Chapter 5. An energy model calibration methodology and application with sensitivity analysis for a partially-retrofitted university building


Chapter 6: Assessing evidence-based single-step and staged deep-retrofit towards nearly zero-energy buildings (nZEB) using multi-objective optimisation

6.1 Chapter overview

This chapter presents the evaluation of deep-retrofitting strategies for the case-study building. The assessment was carried out using the calibrated building energy model developed in Chapter 5. The calibrated model determined the impact of different retrofit measures proposed for the case-study building in terms of energy consumption, life-cycle cost and indoor comfort. The base models were prepared to represent the partial-retrofit and pre-retrofit case-study building. A methodological assessment was conducted via three proposed scenarios for the partially-retrofitted university building, where different time periods for retrofit interventions were considered towards assessing single-step and staged retrofit approach. Next, a genetic algorithm (GA) was employed to search for the most-optimal solutions through a multi-objective optimisation. A range of results were available for decision-making from the Pareto front obtained from multi-objective optimisation focused on three objectives i.e. (i) primary energy consumption, (ii) discomfort hours, and (iii) net present value of life-cycle cost. Analysis of results highlighted different possibilities decision-making to retrofit the existing building in a single-step or multiple stages.

The overall methodology of this research (i.e. stakeholder investigation, field-study physical measurements, energy model development, calibration, validation and optimisation) provided a solid basis for assessing the feasibility of deep-retrofit interventions for non-domestic buildings. The impact of selection of deep-retrofit measures was investigated with solar photovoltaics and mechanical ventilation and heat recovery (MVHR) with added focus on indoor environmental quality (IEQ) as it is not well studied in literature. The analysis of single-step and staged-retrofit approaches for long-term renovation strategies is a significant contribution to the state of the art for deep-retrofitting non-domestic buildings. The single-step retrofit approach was found to be better than staged-retrofit in terms of cost, energy and comfort.

This chapter has been submitted to the international journal ‘Energy Efficiency’ and is under review. Sheikh Zuhaib developed the concept, conducted simulations, interpreted the data and prepared the manuscript. The manuscript was co-authored with the primary supervisor Dr. Jamie Goggins who gave advice, directed this research, commented and edited the manuscript at all stages.
Chapter 6. Assessing evidence-based single-step and staged deep-retrofit towards nearly zero-energy buildings (nZEB) using multi-objective optimisation

Abstract
There is a dearth of data and evidence in the literature to assist the industry in determining the most appropriate strategies for large scale deep-retrofitting of non-domestic buildings to achieve healthy low-energy buildings. Support for decision-making and enabling deep-retrofit of these buildings requires approaches such as long-term renovation strategies and building renovation passports. Using a previous field study, this research assesses the impact of single-step and staged-retrofit on improving existing building energy performance and determine an nZEB level with improved comfort and optimal life-cycle costs. The developed methodological framework is applied to a university building built in 1975 (partially-retrofit in 2005) that is expected to be completely retrofitted in 2020. A set of scenarios are analysed for the case-study building using a combination of retrofit measures towards achieving the cost-optimal non-dominated solutions (Pareto front) based on multiple-objective optimisation for the decision-maker. The results highlight that a single-step retrofit can achieve a reduction of up to 60% in primary energy consumption and reduction of 38% in discomfort hours. The findings also indicate that nZEB performance with the primary energy consumption in the range of ~75-90 kWh/m²/yr (with plug-loads) can be achieved cost-effectively through single-step deep-retrofit for a university building. Results highlighted the inability to achieve higher energy performance or improved comfort in two-stages relative to completing a deep-retrofit in a single stage. The results aim to contribute to the existing debate on the economic and environmental feasibility in realising long-term renovation strategies for existing non-domestic buildings, especially university buildings.

6.2 Introduction
Europe is facing a multi-dimensional challenge in the renovation sector where it seeks (i) to double the renovation rate across Europe from 1.2% to 2-3% (higher for public sector) until 2030, (ii) to achieve nearly zero-energy buildings (nZEBs) and (iii) to accelerate deep-retrofit/renovation [1]. There are various deep-retrofit/renovation terminologies or definitions. In European definitions, deep-retrofit/renovation commonly implies a reduction in the final energy consumption to a magnitude of 75% (heating, cooling, ventilation and hot water), whereas in the US it is generally understood as the reduction in the range of 30-50% (including plug-loads) [2], [3]. However, these ranges may vary based on different climate zones, building types and loads.
Globally, the building sector final energy consumption was doubled from 1971 to 2010, reaching 2,794 million tonnes of oil equivalent (Mtoe) [4] and in Europe, it accounts for 40% of the total energy consumption [5]. The European Parliament in the last two decades introduced Directives such as 2002/91/EC [6], 2009/28/EC [7], 2010/31/EU [5], and 2012/27/EU [8] that direct the member states to take measures within a definitive time period to reduce the final energy consumption of buildings. Within this purview, the Energy Performance of Building Directive (EPBD) Recast (2010/31/EU) focused on using renewable energy resources for energy supply to buildings to reduce the impact on non-renewable resources. Article 9 of the EPBD recast also directs that all new buildings must be nZEBs by the end of 2020 and all public buildings by the end of 2018. The EPBD recast (2010/31/EU) recommends setting up of cost-optimal minimum energy performance requirements for existing buildings. This was further amended in 2018 [9] to transform existing buildings into nZEBs, in particular by increasing deep-retrofits and using long-term renovation strategies to achieve the 2050 goals of having a low and zero-emission building stock [10]. National Energy Performance Certificates (EPC) are the primary source of data on the energy performance of the EU building stock and an analysis of 66% of EU total floor area indicates that 97% of the building stock must be upgraded to achieve 2050 decarbonisation goals [11]. Building renovation roadmaps or passports (long-term 10-20yrs.) have been tested for planning step-by-step or staged-renovation in the domestic building sector for achieving deep-retrofit demonstrated through four case studies in Flanders, France, Germany and Denmark, but their viability for the non-domestic sector is yet to be understood [12]. According to the EPBD, Article 2.2 defines nZEB as “a building that has very high energy performance that has nearly zero or very low amount of energy required should to a very significant extent be covered by energy from renewable sources, including renewable energy produced on-site or nearby” [5].

The existing building stock of Europe consists of approximately 60% of buildings built after the Second World War (1960s-1980s) [13]. The non-residential building stock in Europe accounts for 25% of the total floor area [13]. Educational buildings are the largest share of existing non-domestic buildings in Europe constructed prior to 1980 [1]. The thermal energy efficiency of buildings gained importance after the energy crises of the 1970’s in various legislations across Europe [13] and since then, a focus of EU member states has been to retrofit existing buildings and achieve cost-optimal energy performance. For non-domestic buildings particularly, the huge investment costs are identified as a major barrier in realising the full potential of deep-retrofits [14]. Generally, due to large floor/envelope area, expensive energy
systems and budget constraints, these buildings are being retrofitted in ‘piecemeal’ or ‘single measures’ (e.g. double glazing/ thermal insulation/heating system) and these retrofit interventions are often not supported by detailed investigations that fall short of performance targets [1].

6.3 Background

6.3.1 Single-step or staged deep-retrofit

For non-domestic buildings, the energy and environmental performance vary with building typologies, construction technology and their age. Adequately planned deep-retrofits can render energy savings, cost-effectiveness, improved life-cycle and improved indoor comfort [15]. To achieve EU and national targets for energy and greenhouse gas emissions reductions, it is ideal to perform a single-step retrofit. However, in reality, the financial feasibility and logistics can limit the owners’ ability to achieve complete retrofit in a single-step, especially for large non-domestic buildings [14]. Approximately 80-90% of retrofits are applications of only a set of retrofit measures instead of a complete renovation strategy [15]. It is imperative to take deep-retrofit measures in the initial stage rather than at later stages (20-30 yrs.), as most of the building components have a service life of 30-60 yrs [16] and would need to be replaced in later stages which may not be cost-effective. Often, decision-making in setting up retrofit measures for staged-retrofits is complex and requires careful planning to avoid effects that restrict further savings for future interventions in additional stages. The Passive House Institute (PHI) highlighted the European potential in increasing the performance of buildings that significantly impacted the adoption of nearly zero-energy buildings (nZEBs) [15].

Addressing the low-hanging fruits through ad-hoc or partial-retrofits is a common approach; however, it is not ideal to achieve better performance for non-domestic buildings, as it may or may not improve indoor environmental quality (IEQ) conditions [14]. Therefore, planned staged-retrofits for users may improve building performance by reducing upfront costs and distribution of investment costs over a period. The targets for each stage are pre-determined and the impacts are known in advance. However, the staged-retrofit approach may entail certain risks compared to single-step retrofit approaches such as a change in the intended use, function, technology and economic viability. An example in Figure 6.1 shows the difference between both the approaches. Long-term deep energy savings may be achieved with these approaches that are meant to encourage building owners. Choice of single-step or staged deep retrofit can
be determined by analysis of these approaches for specific buildings using state-of-art simulation tools and multi-objective optimisation as it would involve analysis of numerous retrofit measures [17].

<table>
<thead>
<tr>
<th>Stage</th>
<th>Year</th>
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<th>Single-step retrofit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stage-1</td>
<td>1</td>
<td>façade, windows, air-tightness, lighting</td>
<td>façade, windows, air-tightness, lighting, roof, ventilation systems, heating systems, Renewable Energy Systems</td>
</tr>
<tr>
<td>Stage-2</td>
<td>15</td>
<td>roof, ventilation systems</td>
<td></td>
</tr>
<tr>
<td>Stage-3</td>
<td>30</td>
<td>heating systems, Renewable Energy Systems</td>
<td></td>
</tr>
</tbody>
</table>

Figure 6.1 An example of a comparison between single-step and staged deep-retrofit

6.3.2 Selection of deep-retrofit measures using simulation and optimisation

With the complex interaction of the building systems and new emerging technologies, it is fundamental to select the best solution for the retrofit of an existing building in the initial stage. Improving existing building performance holistically involves the study of relationships between occupant comfort, building operation, and the environment. These can be better understood by the use of advanced building energy simulation and optimisation tools. For the design of energy-efficient or nearly-zero energy buildings, a range of tools are being coupled for analyses of the impact of multiple retrofit measures on cost, comfort and energy and are also available in the form of energy retrofit toolkits that guide in the selection of retrofit measures [18]. Several softwares that are used in these toolkits for simulation of energy performance, work on transient relationships of heat transfer [19] and these include EnergyPlus [20], e-Quest and DOE-2 [21], IES- VE [22], TRNSYS [23]. Many platforms are popular in the industry and the selection of particular transient simulation software also depends on the user’s experience and application criteria [24]. Most of the tools developed for retrofit analysis only offer scenario by scenario analysis that offers limited search space and takes more time. The user is unable to analyse a large number of scenarios and limits the capability of these tools to find optimal solutions. To address this approach, parametric and optimisation tools are being used by researchers where the effect of a large number of parameters and simulations can be conducted, and multiple scenarios can be evaluated. The optimisation methods are divided into three categories (i) numerical methods such as calculus-based methods, (ii) enumerative methods such as dynamic programming and (iii) guided random search techniques with single
or multiple point search [25]. Among the guided random search techniques, genetic algorithms (GA) are commonly used in retrofit analyses and these are capable of multi-objective optimisation (MOO). Several other optimisation approaches being used by researchers automate the analyses for optimal solutions are particle-swarm optimisation (PSO), ant colony optimisation (ACO) and Bayesian optimisation (BO) [26]–[29]. However, these approaches are computationally expensive and can be time consuming. Multi-objective optimisation and its strengths has been demonstrated through many retrofit studies [30]–[34], where objective functions such as total annual energy consumption, life-cycle costs (LCC), annual global warming potential (GWP) and predicted percentage of dissatisfaction (PPD) were used to optimise the retrofit interventions in the buildings, focusing on building façade, renewables systems and operation.

### 6.3.3 Cost-optimality and nZEB performance for non-domestic retrofits

The push to achieve nearly zero-energy performance for the new domestic and non-domestic buildings post introduction of European directives has been very significant throughout the EU [35]. However, for existing non-domestic buildings most of the EU member states have either yet to define the nZEB performance requirements or they are under development. From the last update available from 2015, only Austria, Belgium (Brussels), Bulgaria, Cyprus, Czech Republic, Denmark, France, Latvia and Slovenia had outlined the nZEB definitions based on maximum primary energy consumption (heating, cooling, domestic hot-water, air-conditioning and lighting) being the main indicator for some of the existing non-domestic buildings such as schools, office and hospitals [36]. Due to different calculation methodologies, climatic zones and building typologies, the primary energy requirements vary from 0 to 250 kWh/m²/yr within the EU for existing buildings [36]. D’Augustino et. al [37] highlights the necessity of more information and measures to establish better nZEB goals by the EU member states for specific building typologies in the non-domestic sector. On the other hand, varied research methodologies for retrofits are being tested on different case-studies of existing non-domestic buildings to achieve the cost-optimal performance [38]–[40]. This also brings to notice that achieving nZEB performance may not be cost-optimal for all typologies of non-domestic buildings due to huge variations in building use, plug loads, operation and control. In Ireland, when conducting major renovations on existing non-domestic buildings (i.e. defined as when more than 25% of the envelope is retrofitted), nZEB performance is deemed achieved by proving that the retrofit measures result in the cost-optimal solution [41]. It is imperative that
the understanding of cost-optimality and nZEB performance must be outlined and studied through best practices to quantify the energy and cost balance. Zangheri et al. [42] studied the cost-optimality to achieve nZEB performance level for existing buildings on various building typologies (domestic and non-domestic) built during 1960-70s in different European climatic conditions and found that energy saving potential of cost-optimal solutions was in the magnitude of 36-88% (primary energy). It is observed that the EU cost-optimal methodology [43] mainly focuses on the lower cost curve, but other variants also offer better environmental value with higher global costs and may become cost-optimal with the support of incentives from member states [42].

No studies were found in the literature that compared the impact of single-step and staged deep-retrofits on non-domestic building performance in terms of cost, energy and comfort aiming to achieve the nZEB level. The main objective of this research is to show how single-step or staged deep-retrofit concepts may affect the decision-making through a partially retrofitted case study building using multi-objective optimisation (MOO). To understand the differences, a calibrated model of the case study is used for transient simulations and analysed for three-major scenarios based on the period of retrofit.

6.4 Methodology

The proposed methodology assesses the impact of the single-step and staged-retrofit using multi-objective optimisation (MOO) and is demonstrated through a case study of an existing building built in 1975 and analysed by the authors in the previous research [44]. A whole building energy simulation model of the case study was developed by the authors [45] where an exhaustive sensitivity analysis (Morris sampling) and automated-calibration was conducted to achieve a reliable calibrated and validated model. Retrofit measures were evaluated using building simulation models of the case study building and identifying appropriate deep-retrofit solution packages to achieve the cost-optimal and nZEB performance level for different scenarios as shown in the methodological framework (Figure 6.2). Through the analysed scenarios, it was also studied for the case study building, whether, saving the investment in 2005 for a single-step retrofit of 2020 would have been an effective strategy or the actual choice of partial-retrofit in 2005 with deep-retrofit planned in 2020 was better. Retrofit measures to achieve cost-optimal nZEB performance by completing deep-retrofit of the partial-retrofit building in 2020 were also investigated. The retrofit measures considered were a combination
of load reduction measures, upgrade of the building envelope, operation and control, and installation of renewable energy systems.

![Figure 6.2 Methodological framework](image)

The methodology used a calibrated base model of the existing partially-retrofitted building and a model of the original pre-retrofitted building. The retrofit solution packages for upgrading the building are representative of typical interventions used for these types of buildings. The achieved cost-optimal performance is compared to the whole building cost-optimal level of 124 kWh/m\(^2\)/yr under ‘major renovations’ defined in Part-L of Irish building regulations [41] for other naturally ventilated non-domestic buildings. The presented framework is divided into three main scenarios with certain assumptions for assessing the impact of retrofit measures and cost-optimal requirements to achieve nZEB performance.

(i) **Scenario I**: In this scenario, it is assumed that the calibrated base model (partial-retrofit) [44] can be back-dated through informed adjustments to the model input parameters to represent the pre-retrofit stage (original building model) and yield reasonably accurate predictions when fully retrofitted in 2020. These models were created in EnergyPlus [20] using OpenStudio [46]. All new interventions are investigated through MOO on the original building model for deep-retrofit in a single-stage.

(ii) **Scenario II**: In this scenario, the original building model is retrofitted in two-stages. The first-stage corresponds to the retrofit interventions undertaken in 2005. Further, in the second-
Chapter 6. Assessing evidence-based single-step and staged deep-retrofit towards nearly zero-energy buildings (nZEB) using multi-objective optimisation

stage, additional interventions are planned for 2020 on the calibrated base model to improve the existing building performance to cost-optimal and nZEB level. This scenario allows assessing the application of retrofit measures in two-stages.

(iii) Scenario III: Previous retrofit interventions undertaken in 2005 to the building were not considered in the further planning of retrofit in 2020 in this scenario. All new interventions were explored for cost-optimality and to reach the nZEB performance levels representing a single-step retrofit to the existing building (calibrated base model).

The methodological framework enables comparison of multiple scenarios in efficient computational time using MOO through the process shown in Figure 6.3. As presented in the literature, the identification of cost-optimal retrofit measures is a complex and multi-objective problem. Therefore, retrofit packages are developed by analysing the Pareto front for the cost-optimal and the nZEB solutions. The MOO runs genetic algorithm to determine the best package of solutions from a huge number of retrofit measures. The main objectives of the investigation included (a) primary energy consumption (PEC) [kWh/m²/yr] (heating, ventilation, auxiliary, lighting and plug-loads), (b) area-weighted discomfort hours (DH) [%] based on simple ASHRAE 55 [47] and (c) net present value (NPV) of life-cycle costs (LCC) [€/m²] for multiple retrofit packages. Generally, for PEC calculations plug loads are not included in the calculations. However, they represent a major part of the total electricity consumption of the non-domestic buildings and thus they are included in the calculations.

![Figure 6.3 Multi-objective optimisation (MOO) process for identification of deep-retrofit packages](image)

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For computational MOO, the building energy simulation tool EnergyPlus [48] was coupled with jEPlus+EA [49]. EnergyPlus was used for dynamic energy simulations, whereas jEPlus+EA environment was used for setting up the MOO using NSGA-II [50], the definition of parameters, their ranges and extraction of results from the simulations and their comparison.

6.5 Case Study

The outlined methodology is applied to a case study building built in 1975 and partially-retrofitted in 2005 in the campus of the National University of Ireland, Galway, Ireland. The building consists of typical zones such as single offices, post-graduate researcher rooms, conference rooms, lecture rooms and laboratories. In total, there are 25 occupied zones in the building, as shown in Figure 6.4 with the retrofitted and non-retrofitted zones highlighted. The general features of the case study building are given in Table 6.1. The university plans to retrofit the building to nZEB performance level by 2020.

![Figure 6.4 Floor plan of the case study building](image)
Chapter 6. Assessing evidence-based single-step and staged deep-retrofit towards nearly zero-energy buildings (nZEB) using multi-objective optimisation

Table 6.1 Primary features of the case study building

<table>
<thead>
<tr>
<th>Building parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shape of building</td>
<td>Rectangular</td>
</tr>
<tr>
<td>Length (North to South)</td>
<td>42.15 m</td>
</tr>
<tr>
<td>Width (East to West)</td>
<td>12.7 m</td>
</tr>
<tr>
<td>True North</td>
<td>50°</td>
</tr>
<tr>
<td>Total number of floors</td>
<td>2</td>
</tr>
<tr>
<td>Ground floor height (including plenum)</td>
<td>3.4 m</td>
</tr>
<tr>
<td>First floor height (including plenum)</td>
<td>4.12 m</td>
</tr>
<tr>
<td>Gross building volume</td>
<td>4048.46 m$^3$</td>
</tr>
<tr>
<td>Total floor area</td>
<td>1073.15 m$^2$</td>
</tr>
<tr>
<td>Conditioned floor area</td>
<td>1073.15 m$^2$</td>
</tr>
<tr>
<td>Roof area</td>
<td>563.58 m$^2$</td>
</tr>
<tr>
<td><strong>Gross Window-Wall Ratio</strong></td>
<td></td>
</tr>
<tr>
<td>East (45° to 135°)</td>
<td>34.42%</td>
</tr>
<tr>
<td>West (225° to 315°)</td>
<td>40.91%</td>
</tr>
<tr>
<td>North (315° to 45°)</td>
<td>49.83%</td>
</tr>
<tr>
<td>South (135° to 225°)</td>
<td>0</td>
</tr>
</tbody>
</table>

A detailed building audit was conducted in the previous research by the authors along with the Indoor Environmental Quality (IEQ) assessment from 2016-17 [44]. The data collected was used to develop a building energy base model as per ASHRAE 209 [51] and can be categorised as follows:

a) Geometrical data: dimensions, shape, size of the building and other characteristics.

b) Thermo-physical properties: building envelope composition, components and details.

c) Use of the building: internal loads and schedules -occupancy, equipment, lighting and HVAC.

d) Systems: HVAC systems and their sizes for all the conditioned zones.

The thermal zones were developed using the detailed audit information and specifications in OpenStudio [46] (GUI for EnergyPlus) as summarised in Table 6.2. The weather file was prepared using data from the local weather station installed above the building (N53° 16’47” W9° 03’37” ) [52]. A CPU with Intel® Xeon® X5690 @ 3.47 GHz processor and RAM of 24.0 GB was used for all the simulations. To analyse the retrofit measures on the model it must be calibrated to meet the acceptance criteria set by ASHRAE Guideline 14 [53]. The developed base model was further calibrated using automated calibration (GA optimisation) of 25 parameters in two-stages following a sensitivity analysis using an extensive set of utility and indoor temperature data of one year (2016-17) [45]. Both the calibration stages were validated to meet the acceptance criteria for monthly calibration ($CvRMSE_{monthly} = 15\%$ and $NMBE_{monthly} = ± 5\%$) and hourly calibration ($CvRMSE_{monthly} = 30\%$ and $NMBE_{monthly} = ± 10\%$). In the results
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of final calibration, a CvRMSE\textsubscript{monthly} of 14.4% and NMBE\textsubscript{monthly} of 2.5% was achieved for total electricity consumption and a CvRMSE\textsubscript{monthly} of 9.0% and NMBE\textsubscript{monthly} of -4.6% for heating energy consumption. For indoor air temperature for all zones of the building the CvRMSE\textsubscript{hourly} varied between 17.0-25.6% and NMBE\textsubscript{hourly} between -2.9 to -10.0%. The calibration results highlighted that accurate modelling of old (30-40yrs.) existing buildings is challenging as the criteria were only just satisfied.

Table 6.2 Description of thermal zones in calibrated model

<table>
<thead>
<tr>
<th>Room</th>
<th>Type of room</th>
<th>Glazing &amp; Orientation</th>
<th>Status</th>
<th>Area [m²]</th>
<th>Occupant density [person/ m²]</th>
<th>Lighting load [W/m²]</th>
<th>Total equipment load [W/m²]</th>
<th>Infiltration rate [ACH]</th>
<th>Heating Setpoint [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>G.0</td>
<td>Single office</td>
<td>Double (SW)</td>
<td>R</td>
<td>12.59</td>
<td>0.08</td>
<td>14.77</td>
<td>70.91</td>
<td>1.47</td>
<td>23</td>
</tr>
<tr>
<td>G.1</td>
<td>Single office</td>
<td>Double (SW)</td>
<td>R</td>
<td>12.09</td>
<td>0.08</td>
<td>14.77</td>
<td>70.91</td>
<td>1.47</td>
<td>23</td>
</tr>
<tr>
<td>G.2</td>
<td>Single office</td>
<td>Single (SW)</td>
<td>NR</td>
<td>12.18</td>
<td>0.08</td>
<td>14.77</td>
<td>70.91</td>
<td>2.63</td>
<td>23</td>
</tr>
<tr>
<td>G.3</td>
<td>Conference room</td>
<td>Single (SW)</td>
<td>NR</td>
<td>30.47</td>
<td>0.31</td>
<td>14.20</td>
<td>13.4</td>
<td>2.63</td>
<td>21</td>
</tr>
<tr>
<td>G.4</td>
<td>Single office</td>
<td>Single (SW)</td>
<td>NR</td>
<td>12.33</td>
<td>0.08</td>
<td>14.77</td>
<td>70.91</td>
<td>2.63</td>
<td>23</td>
</tr>
<tr>
<td>G.5</td>
<td>Single office</td>
<td>Single (SW)</td>
<td>NR</td>
<td>12.16</td>
<td>0.08</td>
<td>14.77</td>
<td>70.91</td>
<td>2.63</td>
<td>23</td>
</tr>
<tr>
<td>G.6</td>
<td>Single office</td>
<td>Single (SW)</td>
<td>NR</td>
<td>12.38</td>
<td>0.08</td>
<td>14.77</td>
<td>70.91</td>
<td>2.63</td>
<td>23</td>
</tr>
<tr>
<td>G.7</td>
<td>Single office</td>
<td>Double (SW)</td>
<td>R</td>
<td>18.18</td>
<td>0.06</td>
<td>14.77</td>
<td>70.91</td>
<td>1.47</td>
<td>23</td>
</tr>
<tr>
<td>G.8</td>
<td>Single office</td>
<td>Single (SW)</td>
<td>NR</td>
<td>18.6</td>
<td>0.05</td>
<td>14.77</td>
<td>70.91</td>
<td>2.63</td>
<td>23</td>
</tr>
<tr>
<td>G.9</td>
<td>Single office</td>
<td>Single (SW)</td>
<td>NR</td>
<td>11.96</td>
<td>0.08</td>
<td>14.77</td>
<td>70.91</td>
<td>2.63</td>
<td>23</td>
</tr>
<tr>
<td>G.10</td>
<td>Single office</td>
<td>Single (SW)</td>
<td>NR</td>
<td>12.14</td>
<td>0.08</td>
<td>14.77</td>
<td>70.91</td>
<td>2.63</td>
<td>23</td>
</tr>
<tr>
<td>G.11</td>
<td>Single office</td>
<td>Single (NW)</td>
<td>NR</td>
<td>18.7</td>
<td>0.05</td>
<td>14.77</td>
<td>70.91</td>
<td>2.63</td>
<td>23</td>
</tr>
<tr>
<td>G.12</td>
<td>Single office</td>
<td>Double (NW)</td>
<td>R</td>
<td>27.01</td>
<td>0.04</td>
<td>14.77</td>
<td>70.91</td>
<td>1.47</td>
<td>23</td>
</tr>
<tr>
<td>G.13</td>
<td>Conference room</td>
<td>Single (NE)</td>
<td>NR</td>
<td>62.66</td>
<td>0.31</td>
<td>14.20</td>
<td>53.7</td>
<td>2.63</td>
<td>21</td>
</tr>
<tr>
<td>G.14</td>
<td>Post-grad room</td>
<td>Double (NE)</td>
<td>R</td>
<td>36.6</td>
<td>0.17</td>
<td>17.10</td>
<td>65.2</td>
<td>1.47</td>
<td>23</td>
</tr>
<tr>
<td>G.15</td>
<td>Computer lab</td>
<td>Single (NE)</td>
<td>NR</td>
<td>44.72</td>
<td>0.24</td>
<td>14.49</td>
<td>62.3</td>
<td>2.63</td>
<td>22</td>
</tr>
<tr>
<td>G.16</td>
<td>Post-grad room</td>
<td>Double (NE)</td>
<td>R</td>
<td>53.35</td>
<td>0.17</td>
<td>17.10</td>
<td>65.2</td>
<td>1.47</td>
<td>23</td>
</tr>
<tr>
<td>G.17</td>
<td>Post-grad room</td>
<td>Single (NE)</td>
<td>NR</td>
<td>26.82</td>
<td>0.15</td>
<td>17.10</td>
<td>23.4</td>
<td>2.63</td>
<td>23</td>
</tr>
<tr>
<td>G.18</td>
<td>Single office</td>
<td>Single (NE)</td>
<td>NR</td>
<td>17.99</td>
<td>0.06</td>
<td>14.79</td>
<td>70.91</td>
<td>2.63</td>
<td>23</td>
</tr>
<tr>
<td>GF Corridor</td>
<td>Corridor</td>
<td>-</td>
<td>-</td>
<td>83.66</td>
<td>-</td>
<td>6.89</td>
<td>-</td>
<td>1.47</td>
<td>-</td>
</tr>
<tr>
<td>F.1</td>
<td>Lecture room</td>
<td>Double (SW)</td>
<td>R</td>
<td>91.2</td>
<td>0.62</td>
<td>12.47</td>
<td>3.22</td>
<td>1.47</td>
<td>24</td>
</tr>
<tr>
<td>F.2</td>
<td>Lecture room</td>
<td>Double (SW)</td>
<td>R</td>
<td>73.97</td>
<td>0.62</td>
<td>12.47</td>
<td>3.22</td>
<td>1.47</td>
<td>24</td>
</tr>
<tr>
<td>F.3</td>
<td>Lecture room</td>
<td>Double (SW)</td>
<td>R</td>
<td>89.03</td>
<td>0.62</td>
<td>12.47</td>
<td>3.22</td>
<td>1.47</td>
<td>24</td>
</tr>
<tr>
<td>F.4</td>
<td>Lecture room</td>
<td>Double (SW)</td>
<td>R</td>
<td>88.87</td>
<td>0.62</td>
<td>12.47</td>
<td>3.22</td>
<td>1.47</td>
<td>24</td>
</tr>
<tr>
<td>F.5</td>
<td>Lab</td>
<td>Double (NW)</td>
<td>R</td>
<td>85.89</td>
<td>0.24</td>
<td>11.30</td>
<td>3.05</td>
<td>1.47</td>
<td>22</td>
</tr>
<tr>
<td>F.6</td>
<td>Lab</td>
<td>Double (NW)</td>
<td>R</td>
<td>36.89</td>
<td>0.24</td>
<td>11.30</td>
<td>3.05</td>
<td>1.47</td>
<td>22</td>
</tr>
<tr>
<td>FF Corridor1</td>
<td>Corridor</td>
<td>Double (NE)</td>
<td>R</td>
<td>49.65</td>
<td>-</td>
<td>7.25</td>
<td>-</td>
<td>1.47</td>
<td>-</td>
</tr>
<tr>
<td>FF Corridor2</td>
<td>Corridor</td>
<td>Double (NE)</td>
<td>R</td>
<td>21.08</td>
<td>-</td>
<td>6.83</td>
<td>-</td>
<td>1.47</td>
<td>-</td>
</tr>
</tbody>
</table>

Note: SW- South West, NW- North West, NE- North East, R-Retrofitted, NR-Non-Retrofitted
Chapter 6. Assessing evidence-based single-step and staged deep-retrofit towards nearly zero-energy buildings (nZEB) using multi-objective optimisation

From the previous IEQ assessment (survey and measurements) of the building, the thermal comfort conditions were not satisfactory for the occupants in the building [44]. The presence of thermal bridges was identified using thermal imaging. The occupants also expressed a greater need for improved thermal comfort. Findings also suggested the presence of discomfort due to high infiltration rates (measured from blower-door tests) and single-glazing in non-retrofitted zones. The building is naturally ventilated, and the absence of mechanical ventilation system caused poor indoor air quality (IAQ) in many zones, specially lecture rooms during the winter season due to the high concentration of CO$_2$ and lack fresh air [44]. The lighting system comprises recessed T5 lamps (4x32W) replaced in 2005 in all the zones with no occupancy control. Therefore, the existing building presented many opportunities to reduce energy consumption and improve the indoor environmental comfort based on earlier investigation and these are discussed in further sections.

6.5.1 Base models

To conduct analysis as per the scenarios outlined in the methodology two-base models were required, a calibrated base model and original building model. Since the calibrated base model (partial-retrofit) was developed earlier [45], a model representing pre-retrofit conditions was required for understanding the impact of retrofit measures applied in 2005. As shown in Table 6.3, the input parameters of the calibrated based model (partial-retrofit) were adjusted to represent the pre-retrofit condition of the building. The adjustments involved primarily rolling back the building upgrades undertaken in 2005 and mainly involved removal of wall insulation board, double-glazing to single-glazing, increased infiltration rates to match current non-retrofitted zones, reduced heating system efficiency for replacement of baseboard units and increased lighting loads to match consumption of T8 lamps (high energy consumption and radiant heat). Equipment loads were assumed to be the same for the pre-retrofit building and were included in the primary energy consumption calculation in this study.

A comparison of energy and comfort performance of both the models is given in Table 6.3. The analysis highlights that the primary energy consumption (PEC) of the pre-retrofit building is 39.5 kWh/m$^2$/yr higher than the partial-retrofit building. The comparison also shows that the percentage of area weighted discomfort hours have a small difference, indicating the low impact of partial-retrofit in 2005 on indoor thermal comfort. Considering the poor performance of the existing building after partial-retrofit, a further intervention is required to improve the
energy performance and comfort. Therefore, a set of proposed retrofit measures are identified together with their cost data and presented in the next section.

Table 6.3 Detailed input parameters and performance of the pre-retrofit model compared to partial-retrofit model

<table>
<thead>
<tr>
<th>Model component</th>
<th>Input parameters</th>
<th>Unit</th>
<th>Partial retrofit-building</th>
<th>Pre-retrofit building</th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Calibrated base model (B0)</td>
<td>Original building model (A0)</td>
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<tr>
<td>External wall mass insulation</td>
<td>Conductivity</td>
<td>W/m-K</td>
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<td>0.049</td>
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<tr>
<td></td>
<td>Thickness</td>
<td>m</td>
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<tr>
<td></td>
<td>Density</td>
<td>kg/m³</td>
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<td>265</td>
</tr>
<tr>
<td></td>
<td>Specific heat</td>
<td>J/kg-K</td>
<td>836.8</td>
<td>836.8</td>
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<td>External wall board insulation</td>
<td>Conductivity</td>
<td>W/m-K</td>
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<td>Absent*</td>
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<td></td>
<td>Specific heat</td>
<td>J/kg-K</td>
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<td>Density</td>
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<td>Specific heat</td>
<td>J/kg-K</td>
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<td>836.8</td>
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<td>Envelope</td>
<td>Air infiltration (Retrofitted zones)</td>
<td>ach</td>
<td>1.47</td>
<td>2.63*</td>
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<td></td>
<td>Air infiltration (Non-retrofitted zones)</td>
<td>ach</td>
<td>2.63</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ventilation rate- Single offices</td>
<td>ach</td>
<td>4.00</td>
<td>4.00</td>
</tr>
<tr>
<td></td>
<td>Ventilation rate- Post grad room</td>
<td>ach</td>
<td>4.00</td>
<td>4.00</td>
</tr>
<tr>
<td></td>
<td>Ventilation rate- Conference room</td>
<td>ach</td>
<td>4.00</td>
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<td>Ventilation rate- Lab</td>
<td>ach</td>
<td>5.00</td>
<td>5.00</td>
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<td></td>
<td>Ventilation rate- Lecture room</td>
<td>ach</td>
<td>3.38</td>
<td>3.38</td>
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<td>Windows</td>
<td>Solar transmittance (SHGC) - double glazing</td>
<td>-</td>
<td>0.754</td>
<td>absent*</td>
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<td></td>
<td>Solar transmittance (SHGC) - single glazing</td>
<td>-</td>
<td>0.828</td>
<td>0.828</td>
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<td></td>
<td>Visible transmittance - double glazing</td>
<td>-</td>
<td>0.807</td>
<td>absent*</td>
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<td></td>
<td>Visible transmittance - single glazing</td>
<td>-</td>
<td>0.899</td>
<td>0.899</td>
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<td>Double glazing U-value</td>
<td>W/m²K</td>
<td>2.57</td>
<td>absent*</td>
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<tr>
<td></td>
<td>Single glazing U-value</td>
<td>W/m²K</td>
<td>5.46</td>
<td>5.46</td>
</tr>
<tr>
<td></td>
<td>Window frame</td>
<td>W/m²K</td>
<td>3.22</td>
<td>6.27</td>
</tr>
<tr>
<td>Shading</td>
<td>Vertical blinds- conductivity</td>
<td>W/m-K</td>
<td>0.20</td>
<td>0.2</td>
</tr>
<tr>
<td>Internal Loads</td>
<td>Equipment loads- Single office</td>
<td>W/m²</td>
<td>70.91</td>
<td>70.91</td>
</tr>
<tr>
<td></td>
<td>Equipment loads- Post grad room</td>
<td>W/m²</td>
<td>65.20</td>
<td>65.20</td>
</tr>
<tr>
<td></td>
<td>Equipment loads- Conference</td>
<td>W/m²</td>
<td>53.70</td>
<td>53.70</td>
</tr>
<tr>
<td></td>
<td>Equipment loads- Lab</td>
<td>W/m²</td>
<td>3.05</td>
<td>3.05</td>
</tr>
<tr>
<td></td>
<td>Equipment loads- Lecture room</td>
<td>W/m²</td>
<td>3.22</td>
<td>3.22</td>
</tr>
</tbody>
</table>
Chapter 6. Assessing evidence-based single-step and staged deep-retrofit towards nearly zero-energy buildings (nZEB) using multi-objective optimisation

| Lighting Power Density - Single office | W/m² | 14.77 | 25.00* |
| Lighting Power Density - Post grad room | W/m² | 17.10 | 29.00* |
| Lighting Power Density - Conference | W/m² | 14.20 | 24.00* |
| Lighting Power Density - Lab | W/m² | 11.30 | 19.00 |
| Lighting Power Density - Lecture room | W/m² | 12.47 | 21.00* |
| Occupant density- Single office | person/m² | 0.07 | 0.07 |
| Occupant density- Post grad room | person/m² | 0.17 | 0.17 |
| Occupant density- Conference | person/m² | 0.31 | 0.31 |
| Occupant density- Lab | person/m² | 0.24 | 0.24 |
| Occupant density- Lecture room | person/m² | 0.62 | 0.62 |
| Indoor Heating setpoint-Single | ºC | 23 | 23 |
| Indoor Heating setpoint-Post grad room | ºC | 23 | 23 |
| Indoor Heating setpoint-Conference | ºC | 21 | 21 |
| Indoor Heating setpoint-Lab | ºC | 22 | 22 |
| Indoor Heating setpoint-Lecture room | ºC | 24 | 24 |
| Indoor Heating setpoint-Corridor | ºC | 21 | 21 |
| Lighting heat gain radiant fraction | - | 0.10 | 0.15 |
| Equipment heat gain radiant fraction | - | 0.10 | 0.10 |
| Occupant heat gain radiant fraction | - | 0.30 | 0.30 |
| District heating efficiency | % | 83 | 65* |
| Pump efficiency | % | 90 | 75* |
| Baseboard heating efficiency | % | 90 | 75* |

*Adjustments made in the calibrated model to obtain a pre-retrofit model

### 6.5.2 Proposed retrofit measures and cost data

The proposed retrofit measures are based on the four main action areas after the previous findings i.e. load reduction measures, building envelope, operation and control, and renewable energy systems. The identified retrofit measures together with their initial investments (ex. VAT) are detailed in Table 6.4 and these were applied to the original and partially-retrofitted building models for assessing the three scenarios outlined in the methodology. The proposed retrofit measures have been given an identification number and used for reference in later analysis. The description of thermo-physical properties for the building envelope measures (glazing, wall insulation and roof insulation) are also given and used for performance evaluation in building energy simulation.
### Table 6.4 Proposed retrofit measures for the case study building to achieve the performance objectives

<table>
<thead>
<tr>
<th>Identified retrofit measures</th>
<th>ID</th>
<th>Options</th>
<th>Insulated Glass Unit</th>
<th>Width [mm]</th>
<th>U-value [W/m².K]</th>
<th>U-value with frame [W/m².K]</th>
<th>VT (Visual Transmittance)</th>
<th>SC (Shading Coefficient)</th>
<th>SHGC (Solar Heat Gain Coefficient)</th>
<th>g (Solar Transmittance)</th>
<th>Part-L requirements of U-value [W/m².K]</th>
<th>Investment Cost (ex. VAT)</th>
<th>Incentives or grants***</th>
</tr>
</thead>
<tbody>
<tr>
<td>Replacement of single glazing with double glazing</td>
<td>G1</td>
<td>Double glazing (low E, argon filled)</td>
<td>4(16)+4</td>
<td>1.2</td>
<td>1.8</td>
<td>81</td>
<td>0.83</td>
<td>0.72</td>
<td>0.73</td>
<td>1.8</td>
<td>€490</td>
<td></td>
<td>BEC grant (30% funded of IC)</td>
</tr>
<tr>
<td></td>
<td>G2</td>
<td>Double glazing (low E, argon filled)</td>
<td>4(16)+4</td>
<td>1</td>
<td>1.6</td>
<td>70</td>
<td>0.63</td>
<td>0.54</td>
<td>0.55</td>
<td>1.8</td>
<td>€550</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>G3</td>
<td>Double glazing (low E, air filled)</td>
<td>4(16)+4</td>
<td>1.4</td>
<td>2</td>
<td>65</td>
<td>0.5</td>
<td>0.45</td>
<td>0.43</td>
<td>1.8</td>
<td>€400</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>G4</td>
<td>Double glazing (low E, air filled)</td>
<td>4(16)+4</td>
<td>1.3</td>
<td>1.9</td>
<td>66</td>
<td>0.5</td>
<td>0.45</td>
<td>0.43</td>
<td>1.8</td>
<td>€450</td>
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<tr>
<td>Addition of Wall insulation</td>
<td>W1</td>
<td>Metal/wood frame PIR insulation</td>
<td>70</td>
<td>0.314</td>
<td>0.022</td>
<td>140</td>
<td>32</td>
<td></td>
<td></td>
<td>0.35</td>
<td>€290</td>
<td></td>
<td>BEC grant (30% funded of IC)</td>
</tr>
<tr>
<td></td>
<td>W2</td>
<td>Metal/wood frame PIR insulation</td>
<td>60</td>
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<td>32</td>
<td></td>
<td></td>
<td></td>
<td>€282</td>
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<tr>
<td></td>
<td>W3</td>
<td>Metal/wood frame PIR insulation</td>
<td>65</td>
<td>0.338</td>
<td>0.022</td>
<td>150</td>
<td>32</td>
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<td></td>
<td></td>
<td>€280</td>
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<td></td>
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<tr>
<td></td>
<td>W4</td>
<td>Metal/wood frame PIR insulation</td>
<td>55</td>
<td>0.327</td>
<td>0.018</td>
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<td>Replacement of roof insulation</td>
<td>R1</td>
<td>Profiled Metal – 225mm Mineral Wool Insulation</td>
<td>225</td>
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<td>0.033</td>
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<tr>
<td></td>
<td>R2</td>
<td>Profiled Metal – 230mm Mineral Wool Insulation</td>
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<tr>
<td></td>
<td>R3</td>
<td>Profiled Metal-PIR Insulation</td>
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<td></td>
<td>R4</td>
<td>Profiled Metal-PIR Insulation</td>
<td>200</td>
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<td>0.027</td>
<td>1520</td>
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<td>Replacement of more efficient lighting</td>
<td>L1</td>
<td>Recessed light-Louvre (600x600) T5</td>
<td>4x14W</td>
<td>56</td>
<td>85.4</td>
<td>66</td>
<td></td>
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<tr>
<td></td>
<td>L2</td>
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<td>56</td>
<td>73.6</td>
<td>57</td>
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<td>€54.00</td>
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<tr>
<td></td>
<td>L3</td>
<td>LED Panel light (600x600)</td>
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<td>31</td>
<td>100</td>
<td>103</td>
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<td>€97.00</td>
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<td>L4</td>
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<td>120</td>
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<td>OC</td>
<td>Passive Infra-Red occupancy sensor</td>
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<td>SO Single office</td>
<td>19-22</td>
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<td>PG Post-grad rooms</td>
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<td>CF Conference rooms</td>
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<tr>
<td>LC Lecture rooms</td>
<td>19-22</td>
<td></td>
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<table>
<thead>
<tr>
<th>Air-tightness improvement</th>
<th>Zones</th>
<th>Proposed (ACH)²</th>
<th>€/m² of floor²</th>
<th>BEC grant (30% funded of IC)</th>
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<tbody>
<tr>
<td></td>
<td>A1 All zones</td>
<td>1</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>A2 All zones</td>
<td>1.2</td>
<td>7.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>A3 All zones</td>
<td>1.4</td>
<td>7.6</td>
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</table>

<table>
<thead>
<tr>
<th>HVAC system</th>
<th>Dimensions [mm]</th>
<th>Wh/m³</th>
<th>Supplied Air Volume [m³/h]</th>
<th>Total cost</th>
<th>BEC grant (30% funded of IC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MV MVHR (GF &amp; FF) with demand control ventilation (DCV)</td>
<td>750 x 1198 x 2100</td>
<td>0.42</td>
<td>1400</td>
<td>€40,305.90</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>System</th>
<th>Type</th>
<th>Surface area [m²]</th>
<th>No. of PV modules</th>
<th>No. of batteries</th>
<th>No. of inverters</th>
<th>Capacity (PV output)</th>
<th>Total cost²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photovoltaic Array</td>
<td>Polycrystalline</td>
<td>281.7</td>
<td>168</td>
<td>12</td>
<td>6</td>
<td>32.19kWp</td>
<td>€38,890.96</td>
</tr>
</tbody>
</table>

*Funding provided under Better Energy Communities Scheme by SEAI (2018) for public buildings by Irish government [54]

**Solar PV grant provided by SEAI for installation of renewable systems on public buildings [55]

***The total amount of grant per project is limited to €1,000,000 by SEAI

*Based on revised Part-L: Building other than dwellings nZEB requirements (2018)

**Investment costs based on market research by SEAI [56]
Other retrofit measures include improvement in air-tightness and replacement of existing lighting to energy efficient T5 or LED panel lights, along with PIR occupancy sensors. Addition of mechanical ventilation with heat recovery (MVHR) system along with demand control ventilation (DCV) is also proposed to be integrated with existing heating system based on the requirement of improving the IEQ for all the zones on both the floors. Installation of a photovoltaic (PV) system is also proposed on the roof of the building towards achieving nZEB performance. Heating setpoint settings were identified as the main variable having the largest impact on total heating energy consumption of the building [45]. Therefore, adjustment to the operation range of the setpoints was suggested for all the zones based on the standard EN15251 [57]. The investment costs (ex. VAT) were obtained from local suppliers and market research documents available from Sustainable Energy Authority of Ireland (SEAI) [56]. The grant support through initiatives in Ireland such as Better Energy Communities (BEC) [55] and Solar PV grants [55] to deep-retrofit existing buildings from the SEAI was also considered in the cost calculations. The maximum amount available for grants in a single project is limited to €1,000,000 by SEAI [55]. All the retrofit measures are proposed to at least meet the recently revised Part-L (buildings other than dwellings) building regulation requirements outlined for existing non-domestic buildings aiming to achieve whole building cost-optimal performance [41].

### 6.5.3 Simulation, multi-objective optimisation and objective functions

All the scenarios in the methodology are analysed for different retrofit measures using jEPlus+EA coupled with EnergyPlus. The ranges of different input parameters associated with each option for retrofit were based on a number of options under each retrofit measure in Table 6.4. These ranges were defined within jEPlus+EA which runs MOO using Non-dominated Sorting Genetic Algorithm (NSGA-II) that works by maintaining a population of individuals and selection of the fittest to move on to the next generations. The diversity of individual solutions is maintained by crossover and mutation rate. The NSGA-II works on a non-dominated sorting and ranking process of individuals maintaining the spread of solutions and converges into a non-dominated front [50]. Crowding distance is also calculated for each solution to maintain the spread along the front known as the Pareto front.

For each solution during optimisation, jEPlus+EA passes a set of input parameters to an EnergyPlus file (*.idf) which runs the transient simulation and returns the results based on the
defined objectives in a *.rvx file within jEPlus+EA. In this study, three objectives were selected for optimisation which were primary energy consumption [kWh/m²/yr], discomfort hours [%] and net present value of life-cycle cost [€/m²]. No constraints were included in the simulations. All the solutions were obtained through the Pareto-front (3D and 2D) and were equally optimised. However, the selection of specific solution depends on the decision-maker based on the importance given to one objective over the other. The most-optimal solution was selected from the front that was closest to the utopia point [58].

6.5.4 Life-cycle cost calculations

The life-cycle cost analysis was conducted to assess the cost-optimality of retrofit measures with other objectives of energy and comfort. A review period of 30 years was taken for calculations where retrofits are planned in 2020 based on the maximum service life of building systems. A review period of 15 years was taken for the calculations where retrofit was carried out in 2005. The assumptions taken for the LCC calculations are given in Table 6.5. A nominal discount rate of 3.14% is suggested by National Development and Finance Agency (NDFA) to be used for the design, build and operate projects where the effect of inflation is to be considered [59]. Therefore, a rate of 3% was assumed for calculations based on historical records. Based on the historical inflation rates in Ireland, a value of 2% was taken for this study [60]. However, a constant annual energy price escalation of 4% (2% over general inflation) was assumed based on the average historical escalation rates in Ireland [60]. The energy prices used were made available from the university database. The price for electricity sold back to the grid was assumed to be lower than the purchase price based on the micro-generation schemes proposed earlier in Ireland [61].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>From 2005</th>
<th>From 2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>Review period (duration)</td>
<td>15 years</td>
<td>30 years</td>
</tr>
<tr>
<td>Nominal discount rate</td>
<td>3%</td>
<td>3%</td>
</tr>
<tr>
<td>Average inflation rate</td>
<td>2%</td>
<td>2%</td>
</tr>
<tr>
<td>Energy price escalation</td>
<td>4%</td>
<td>4%</td>
</tr>
</tbody>
</table>

**Energy prices**

<table>
<thead>
<tr>
<th></th>
<th>€ 0.0417/kWh</th>
<th>€ 0.0582/kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>District heating</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electricity (purchase)</td>
<td>€ 0.1209/kWh</td>
<td>€ 0.1688/kWh</td>
</tr>
<tr>
<td>Electricity (sell)</td>
<td>€ 0.1100/kWh</td>
<td></td>
</tr>
</tbody>
</table>

*Based on rates available from university database (ex. VAT- 13.5%)

*Energy sold back to the grid
For all the retrofit measures analysed, life-cycle costs included their investment costs, operational energy costs, maintenance and repair costs, and replacement costs. Life-cycle costs are the sum of cash-flows of the retrofit measures expressed in the equation below. The total net present value for life-cycle cost was calculated by equation (6.1):

\[ NPV_{LCC} = \sum IC_{total} + \sum OE_{total} + \sum MR_{total} + \sum Re_{total} \]  

(6.1)

where, \( NPV_{LCC} \) is the total net present value of the life-cycle costs of retrofit measures calculated over a time-period of \( n \) years; \( \sum IC_{total} \) is the total investment costs of the retrofit measures [€]; \( \sum OE_{total} \) are the total operational energy costs during the study period [€]; \( \sum MR_{total} \) are the total costs of the maintenance and repair [€]; \( \sum Re_{total} \) are the total replacement costs of the systems during the study period [€]. The residual costs were not included in the calculation of the NPV in this study.

The total operational energy costs were calculated by equation (6.2).

\[ \sum OE_{total} = OE_{yr} \times \left( \frac{(1+e)}{(d-e)} \right) \left[ 1 - \left( \frac{1+e}{1+d} \right)^n \right] \]  

(6.2)

where \( d \) is the nominal discount rate for LCC calculations; \( e \) is the constant energy price escalation rate; \( n \) is the period under consideration [yr]; \( OE_{yr} \) is the annual operational energy cost [€/yr]

The maintenance and repair costs were calculated for the all retrofit measures by equations (6.3).

\[ \sum MR_{total} = MR_{yr} \times \left( \frac{(1+i)}{(d-i)} \right) \left[ 1 - \left( \frac{1+i}{1+d} \right)^n \right] \]  

(6.3)

where \( MR_{yr} \) is the annual maintenance and repair cost [€/yr] and \( i \) is the general inflation rate.

The replacement costs of retrofit measures were calculated by equation (6.4).

\[ \sum Re_{total} = Re_{yr} \times \left( \frac{1+i}{1+d} \right)^n \]  

(6.4)
where $Re_{yr}$ is the annual replacement costs [€/yr].

The forward value (future value) of $NPV_{LCC}$ is calculated by the relationship given in equation (6.5) using appropriate interest (discount) rate, $i_d$.

$$FV = NPV_{LCC} \times (1 + i_d)^n$$

where FV is the forward value of the net present value for any period under consideration

The results and discussion in the next section are organised following the three scenarios in the methodological framework (Section 6.4) that were applied to the case study building.

### 6.6 Results and discussion

The original building (identified as model A0 in the analysis) (in Table 6.3) was retrofitted in 2005 and the retrofit measures that were applied included (i) replacement of single-glazing to double glazing, (ii) addition of wall insulation, (iii) replacement of T8 lighting, and (iv) airtightness improvement. Effectively, the current calibrated base model (B0) represents the retrofitted building as it currently exists. The technologies such as solar PV and MVHR were not cost-effective prior to 2009 in Ireland [62] and, therefore, they were not included in partial-retrofit based on cost-benefit analysis conducted at that time by the university. Construction cost index (ex.VAT) historical database of Ireland indicates an inflation of 17.9% in the costs of construction labour, material and goods from 2005 to 2017 [58]. The energy price data for 2005 was available from the university database. Therefore, the costs were adjusted to 2005 values for LCC calculations. The cost of replacement of baseboards was not included in calculations, as the cost was funded by a third-party. The total estimated net present value (in 2005 value) of life-cycle costs for the partial-retrofit from 2005 to 2020 (review period 15 years) was €299,307 (€279/m$^2$). Of this, the operational costs were €151,531 and retrofit costs were €147,776, respectively. The reported PEC for the partially retrofitted building was 150 kWh/m$^2$/yr, which is a 20.8% reduction in energy consumption compared to the original building. Furthermore, there was only 3.7% improvement in thermal comfort (i.e. discomfort hours went from 21.6% to 20.8% - see Table 6.3).
6.6.1 Scenario I solutions

It was assumed in this scenario that the case-study building was not partially-retrofitted in 2005. The complete deep-retrofit (single-step) is scheduled in 2020. Therefore, the operational costs that would incur over a 15-year period (2005-2020) when not retrofitted would have been €181,106 (in 2005 value).

Further, the identified retrofit measures (Table 6.4) were applied in different combinations to the original building (model A0) for 2020 (study period of 30 yrs.) that included double-glazing (G1-G4), wall insulation (W1-W4), roof insulation (R1-R4), lighting (L1-L4) and lighting occupancy control (OC), air-tightness improvement (A1-A3), setpoint adjustments (SO, PG, CF, LC, LB), solar photovoltaic (PV) and a mechanical ventilation with heat recovery (MVHR) system. The parameters for LCC calculation were taken as per Table 6.5. A multi-objective optimisation was conducted on the original building model to identify the best set of retrofit measures i.e. deep-retrofit solution package to achieve the cost-optimal nZEB performance levels and comfort. A total of 10 parameters were defined for optimisation creating a search space of 442368. A population of 16, a crossover rate of 1 (100%), and a mutation rate of 0.2 (20%) were used in the genetic algorithm (NSGA-II). The stopping criteria for the optimisation algorithm was set to 50 generations.

3D and 2D-plots were generated for the output parameters for all the retrofit solutions (results) for the minimisation of objectives, as shown for example in Figure 6.5 for the model A1.
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Figure 6.5 3D and 2D pareto fronts for retrofit solution packages for Scenario I (model A1-Table 6)

Three models were used for MOO (i) retrofit measures only (A1) (ii) retrofit measures with PV (A2) and (iii) retrofit measures with PV and MVHR (A3). The 3D and 2D-pareto fronts obtained from the plots highlight the optimal solutions after MOO. The global-optimal solutions were selected from the front that were closest to the utopia point. These solutions from the pareto front are presented in Table 6.6 focusing on the three objectives (minimisation of NPV, DH and PEC) and single-objective (min NPV/min DH/min PEC). The decision-maker has the choice of choosing the deep-retrofit solution package based on the weightage given to the objectives.

For model A1, the global-optimal solution achieved a PEC of 82 kWh/m²/yr, which is 56.7% less than the original building (model A0), DH of 14.0% (i.e. reduction of 35%, compared to original building) and NPV of LCC of €636/m² (with grants in 2020 value). However, the solution with the lowest NPV of €670,240 (€625/m²) (with grants in 2020 value) could only achieve a reduction of 52.6% in PEC compared to the original building. If the original building is not retrofitted in 2020, then an operational cost of €471,216 (in 2020 value) would incur over 30 years. Addition of PV in model A2 delivered reduced operational costs thereby achieving a NPV of LCC of €601/m² (with grants in 2020 value) for the global-optimal solution. A further
addition of MVHR in model A3 did not result in a significant reduction of PEC compared to model A1 and reported similar DH to the global-optimal solutions for model A1 and A2, but incurred an NPV of LCC of €690/m² (with grants) which made it the least cost-effective among the global-optimal solutions for the three models. An additional comparative analysis of indoor air quality (IAQ) in terms of CO₂ concentration after retrofit interventions revealed that in a typical lecture room during an average working week in winters the concentration was 2330ppm for model A1/A2 (with peaks of up to 3600ppm) compared to an average of 1498 ppm for the original building (model A0) due to increased air-tightness. However, using an MVHR regulated the fresh air supply and reduced the concentration to a level of 1542ppm. According to ASHRAE 62.1 [63], a 700ppm concentration above outdoor air is an indicator of poor indoor air quality.

Overall, the retrofit solution packages under model A2 were among the most cost-effective for single-step deep retrofit. An energy consumption of 75 kWh/m²/yr with an NPV of LCC of €634,500 (€591/m²) (in 2020 value) was achieved for ‘min PEC’ and 90 kWh/m²/yr with an NPV of LCC of €616,900 (€575/m²) (in 2020 value) for ‘min NPV’ highlighting a significant energy reduction compared to the original building (A0). With a small difference €17,600 in both NPVs of model A2, a promising goal for cost-optimal nZEB performance that may be achieved in 2020 with a maximum investment of €634,500 in 2020 in a single-step retrofit that ranges between ~75 - 90 kWh/m²/yr (~57-72 kWh/m²/yr excluding plug-loads) for the studied typology of building in Ireland.

NPV (in 2005 value) of operating the building for 45 years from 2005 would be €588,367 (€548/m²), which includes for deep-retrofit costs (model A2- min PEC) to be undertaken in 2020. This LCC is divided as follows. Total operational cost from 2005-2020 is €181,106 (in 2005 value), retrofit investment in 2020 is €250,261 (in 2005 value) and total operational costs for the retrofitted building from 2020 to 2050 is €157,000 (in 2005 value). On the other hand, if the building was not retrofitted at all, the NPV of LCC from 2020 to 2050 would be €282/m² compared to €379/m² for the retrofitted building (model A2- min PEC) (in 2005 value). Thus, with an additional investment of less than a €100/m² and proper planning the building would have achieved better performance.
Table 6.6 Description of best solutions obtained from the pareto fronts based on the objective functions for scenario I

<table>
<thead>
<tr>
<th>Model</th>
<th>Objectives</th>
<th>Deep-retrofit solutions package</th>
<th>Setpoints</th>
<th>Present Value</th>
<th>Grants - BEC</th>
<th>LCC (NPV of grants)</th>
<th>Performance metrics</th>
<th>NPV of LCC (with grants)</th>
<th>NPV of LCC (with grants)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Original building model</td>
<td>G1, R4, W3, AI, L2, OC</td>
<td>SO(22), PG(19), CF(19), LC(19), LB(18)</td>
<td>471.2</td>
<td>n/a</td>
<td>n/a</td>
<td>471.2</td>
<td>189.49</td>
<td>21.60</td>
</tr>
<tr>
<td></td>
<td>min NPV (cost-optimal energy consumption)</td>
<td>G1, R4, W3, AI, L1, OC</td>
<td>SO(21), PG(19), CF(19), LC(19), LB(18)</td>
<td>330.5</td>
<td>503.7</td>
<td>-</td>
<td>-151.1</td>
<td>-</td>
<td>834.2</td>
</tr>
<tr>
<td></td>
<td>min PEC</td>
<td>G1, R4, W2, AI, L1, OC</td>
<td>SO(19), PG(19), CF(19), LC(19), LB(18)</td>
<td>343.2</td>
<td>467.2</td>
<td>-</td>
<td>-140.2</td>
<td>-</td>
<td>810.4</td>
</tr>
<tr>
<td></td>
<td>min DH</td>
<td>G1, R2, W4, AI, L1, OC</td>
<td>SO(22), PG(22), CF(20), LC(22), LB(18)</td>
<td>298.3</td>
<td>552.4</td>
<td>-</td>
<td>-165.7</td>
<td>-</td>
<td>850.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>global-optimal solution (NPV, PEC, DH)</td>
<td>G1, R4, W3, AI, L2, OC</td>
<td>SO(22), PG(19), CF(19), LC(19), LB(18)</td>
<td>288.9</td>
<td>503.7</td>
<td>37.7</td>
<td>-151.1</td>
<td>-34.5</td>
<td>830.3</td>
</tr>
<tr>
<td></td>
<td>min NPV (cost-optimal energy consumption)</td>
<td>G1, R4, W3, AI, L1, OC</td>
<td>SO(22), PG(19), CF(19), LC(19), LB(18)</td>
<td>286.6</td>
<td>467.3</td>
<td>37.7</td>
<td>-140.2</td>
<td>-34.5</td>
<td>791.6</td>
</tr>
<tr>
<td></td>
<td>min PEC</td>
<td>G1, R4, W2, AI, L1, OC</td>
<td>SO(19), PG(19), CF(19), LC(19), LB(18)</td>
<td>244.6</td>
<td>552.4</td>
<td>37.7</td>
<td>-165.8</td>
<td>-34.5</td>
<td>834.8</td>
</tr>
<tr>
<td></td>
<td>min DH</td>
<td>G1, R2, W4, AI, L1, OC</td>
<td>SO(22), PG(22), CF(20), LC(22), LB(18)</td>
<td>284.4</td>
<td>500.6</td>
<td>37.7</td>
<td>-150.2</td>
<td>-34.5</td>
<td>822.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NV+PV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>global-optimal solution (NPV, PEC, DH)</td>
<td>G1, R4, W3, AI, L2, OC</td>
<td>SO(19), PG(19), CF(19), LC(19), LB(18)</td>
<td>355.1</td>
<td>546.1</td>
<td>37.7</td>
<td>-163.8</td>
<td>-34.5</td>
<td>938.9</td>
</tr>
<tr>
<td></td>
<td>min NPV (cost-optimal energy consumption)</td>
<td>G1, R4, W3, AI, L1, OC</td>
<td>SO(19), PG(19), CF(19), LC(19), LB(18)</td>
<td>366.2</td>
<td>508.6</td>
<td>37.7</td>
<td>-152.6</td>
<td>-34.5</td>
<td>912.5</td>
</tr>
<tr>
<td></td>
<td>min PEC</td>
<td>G1, R4, W4, AI, L3, OC</td>
<td>SO(19), PG(19), CF(19), LC(19), LB(18)</td>
<td>327.2</td>
<td>590.9</td>
<td>37.7</td>
<td>-177.3</td>
<td>-34.5</td>
<td>955.8</td>
</tr>
<tr>
<td></td>
<td>min DH</td>
<td>G1, R4, W4, AI, L2, OC</td>
<td>SO(22), PG(20), CF(19), LC(22), LB(19)</td>
<td>360.6</td>
<td>539.6</td>
<td>37.7</td>
<td>-161.9</td>
<td>-34.5</td>
<td>937.9</td>
</tr>
</tbody>
</table>

*percentage reduction in primary energy consumption compared to the calibrated base model

*percentage reduction in discomfort hours compared to the calibrated base model

*Net present value is in terms of 2020 value
6.6.2 Scenario II solutions

This scenario represents the evaluation of a two-stage retrofit, where the first-stage retrofit was a partial-retrofit completed in 2005 and the second-stage is scheduled for additional retrofit in 2020. A PEC of 150.0 kWh/m²/yr, DH of 20.8% and an NPV of LCC of €299,307 (€279/m²) (in 2020 value) was estimated for the first-stage retrofit that was completed in 2005 (refer Section 6.6 for details).

In the second-stage, the retrofit measures were planned for the case study building in 2020 in addition to the previous measures undertaken in 2005, except for lighting that generally has a service life of 15 years. The calibrated base model (B0) of the building as is in 2005 is used in this stage for MOO. A total of 9 parameters were used for optimisation based on Table 6.4, exploring a search space of 110592. The applied retrofit measures met the Part-L criteria and include replacement of existing single-glazing with double glazing, replacement of roof insulation, air-tightness improvement, setpoint adjustments, replacement of lighting, and the addition of PV and MVHR. The review period for analysis of LCC was 30 years from 2020. The optimal solutions obtained through MOO are shown in Figure 6.6 through 3D and 2D pareto fronts for model B1, while the best solutions from the pareto fronts for models B1 to B3 are given in Table 6.7. The list of solutions gives the decision-maker flexibility to choose the appropriate solution based on the objectives. The population, crossover and mutation rate were same as scenario-I taken for the optimisation algorithm. The stopping criteria was also set to 50 generations.
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Figure 6.6 3D and 2D pareto fronts for retrofit solution packages for Scenario II (model B1- Table 7)

In Table 6.7, the global-optimal solution (model B1) achieved a reduction of 33.8% (99.3 kWh/m²/yr) for PEC and a reduction of 22.7% for DH when compared to the existing partially-retrofitted building (model B0). Addition of PV (model B2) reduced the NPV of LCC to €453/m² (in 2020 value) for the global-optimal solution compared to the solution for model B1. The ‘min PEC’ (model B2) solution had a reduction of 38.5% for PEC and a reduction of 18.8% for DH relative to the existing partially retrofitted building. Application of MVHR (model B3) did improve the DH to 16% (i.e. reduction of 23.3%) for the global-optimal solution, but the costs increased significantly to €552/m² (NPV in 2020 value) due to the operation, high maintenance and replacement costs of the ventilation system making it less cost-effective. However, it improved the IAQ significantly for model B3 compared to solutions for model B1 and B2. For example, in a typical lecture room the CO₂ concentration averaged over a working week was 2204ppm (model B0), 2029ppm (model B1 and B2) and 1470ppm (B3).

Now, comparing results for all the models, B2 presented the most cost-effective solutions. Between the solutions ‘min PEC’ and ‘min NPV’ of B2, an improvement of 8 kWh/m²/yr in PEC was observed with a small difference of €15,500 in LCC (NPV in 2020 value). Thus, min
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PEC can also be considered cost-optimal with lowest energy consumption of approximately 92-100 kWh/m²/yr (~75-82 kWh/m²/yr without plug loads) that can be achieved by a second-stage retrofit, while considering previous retrofit interventions with the maximum investment of €490,500 (€457/m²). Overall, these results highlighted the inability to achieve higher energy performance in two-stages relative to completing a deep retrofit in a single stage.

If the second-stage was planned along with the first-stage in 2005, the investments for the first-stage retrofit was €299,307 (operational cost of €151,531 and retrofit cost of €147,776). For the second-stage the costs in 2005 would be €314,833 (€490,500 in 2020) having operational cost of €166,563 and retrofit cost of €148,270. A total of €614,140 (€572/m²) was needed for investment while planning a two-stage retrofit in 2005 compared to an investment of €588,367 (€548/m²) (in 2005 value) for a single-stage retrofit in 2020 (scenario I). Furthermore, the PEC achieved in this scenario is still higher than scenario I (92-100 kWh/m²/yr compared to 75-90 kWh/m²/yr). Also, with respect to comfort, a significant improvement was not achieved in a two-stage retrofit.
Table 6.7 Description of best solutions obtained from the pareto fronts based on the objective functions for scenario II

<table>
<thead>
<tr>
<th>Model</th>
<th>Objectives</th>
<th>Deep-retrofit solution package</th>
<th>Present Value</th>
<th>Performance metrics</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Measures</td>
<td>Operation al costs</td>
<td>Retrofit investment costs</td>
</tr>
<tr>
<td></td>
<td></td>
<td>[°C]</td>
<td>[k€]</td>
<td>[k€]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B0</td>
<td>Calibrated base model</td>
<td>NV+PV</td>
<td>289.9</td>
<td>n/a</td>
</tr>
<tr>
<td></td>
<td>global-optimal solution</td>
<td>G1, R4, A1, L2, OC</td>
<td>SO(22), PG(19), CF(19), LC(19), LB(18)</td>
<td>345.1</td>
</tr>
<tr>
<td></td>
<td>min NPV (cost-optimal energy consumption)</td>
<td>G3, R1, A1, L2, OC</td>
<td>SO(20), PG(19), CF(19), LC(19), LB(18)</td>
<td>345.7</td>
</tr>
<tr>
<td></td>
<td>min PEC</td>
<td>G1, R4, A1, L4, OC</td>
<td>SO(19), PG(19), CF(19), LC(19), LB(18)</td>
<td>313.2</td>
</tr>
<tr>
<td></td>
<td>min DH</td>
<td>G2, R4, A1, L2, OC</td>
<td>SO(22), PG(19), CF(21), LC(22), LB(20)</td>
<td>357.9</td>
</tr>
</tbody>
</table>

**Notes:**
1. Percentage reduction in primary energy consumption compared to the calibrated base model.
2. Percentage reduction in discomfort hours compared to the calibrated base model.
3. Net present value is in terms of 2020 value.
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6.6.3 Scenario III solutions

In scenario III, the process of retrofitting is assumed without any connect between the two stages and represents an unplanned situation with retrofit occurring in 2005 and 2020. For the retrofit in 2005, the results are the same as outlined in the previous section and it is assumed that the measures taken in 2005 did not deliver the required performance and have also completed their service life except the wall insulation that met the Part-L requirements. Therefore, a complete single-step retrofit is required in 2020 on the partially-retrofitted building (calibrated base model- B0) to achieve cost-optimal nZEB performance with a review period of 30 years. To analyse this scenario an MOO (NSGA-II) was setup with the same population, crossover and mutation rate as previous scenarios. The stopping criteria for optimisation was set to 50 generations. From the results of MOO, 3D and 2D plots were generated, as for example in Figure 6.7, for all the retrofit solutions.

![3D and 2D pareto fronts for retrofit solution packages for Scenario III (model C1 - Table 8)](image)

In Table 6.8, all the solutions are taken from the pareto fronts based on minimisation of objectives and compared to the calibrated base model (B0) performance. The cost-optimal solution for model C2 involved the application of a retrofit solution package with PV and
achieved a reduction of 40.7% (89 kWh/m²/yr) for PEC and 18.4% for DH compared to existing partially retrofitted model (model B0). The NPV of LCC of €497/m² is also the lowest among all the cost-optimal solutions for model C1, C2 and C3. The ‘min PEC’ solution achieved a performance of approximately 76 kWh/m²/yr with reduction of 27.6% in DH and also has small investment difference against ‘min NPV’. Thus, based on these results, a range of approximately 76 to 89 kWh/m²/yr (~58 – 71 kWh/m²/yr without plug loads) can be regarded as cost-optimal nZEB performance achieved in a single-step retrofit on the partially retrofitted building with the total NPV of LCC of €554,600 (€517/m²) (in 2020 values). The global-optimal solution (model C2) is also eligible for cost-optimal nZEB performance when compared to the ‘min PEC’ solution. Again, the addition of MVHR to the model C3 did not yield cost-effective solutions. However, it was effective in improving indoor air quality in the building. For example, a typical lecture room had a weekly average CO₂ concentration of 1684ppm for model C3, as compared to the 2217ppm for model C1 and C2.

To compare this scenario with previous scenarios in 2005, a sum of €355,977 (€332/m²) (€554,600 in 2020) was required for future (2020) with €156,165 for operational cost and €199,812 for retrofit cost. Therefore, if the building was left partially-retrofitted from 2020 to 2050, then the NPV of LCC (in 2005 value) would be €155/m² (model B0) compared to €332/m² for deep-retrofit. The results of the scenario III revealed that a complete single-step retrofit can achieve a higher energy performance similar to scenario I. This can be attributed to the cohesive interactions of different retrofit measures proposed in a single-step retrofit and their analysis at a given time. But these interactions may not be understood effectively in a multi-stage retrofit over a long period of time; mainly due to limitations of future uncertainties in available technologies and solutions.
Table 6.8 Description of best solutions obtained from the pareto fronts based on the objective functions for scenario III

<table>
<thead>
<tr>
<th>Model</th>
<th>Objectives</th>
<th>Deep-retrofit solutions package</th>
<th>Present Value</th>
<th>Performance metrics</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Values</td>
<td>Operating costs</td>
<td>Retrofit investment costs</td>
</tr>
<tr>
<td>B0</td>
<td>Calibrated base model</td>
<td>[°C]</td>
<td>[k€]</td>
<td>[k€]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>259.9</td>
<td>n/a</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C1</td>
<td>global-optimal solution</td>
<td>G1, R3, A1, L2, OC</td>
<td>SO(22), PG(19), CF(19), LC(19), LB(18)</td>
<td>329</td>
</tr>
<tr>
<td></td>
<td>min NPV (cost-optimal energy consumption)</td>
<td>G3, R2, A1, L2, OC</td>
<td>SO(19), PG(19), CF(19), LC(19), LB(18)</td>
<td>338.9</td>
</tr>
<tr>
<td></td>
<td>min PEC</td>
<td>G1, R4, A1, L4, OC</td>
<td>SO(19), PG(19), CF(19), LC(19), LB(18)</td>
<td>296.9</td>
</tr>
<tr>
<td></td>
<td>min DH</td>
<td>G1, R4, A1, L1, OC</td>
<td>SO(22), PG(21), CF(21), LC(22), LB(20)</td>
<td>340.5</td>
</tr>
<tr>
<td>245</td>
<td>global-optimal solution</td>
<td>G1, R4, A1, L2, OC</td>
<td>SO(22), PG(19), CF(19), LC(19), LB(18)</td>
<td>272.5</td>
</tr>
<tr>
<td></td>
<td>min NPV (cost-optimal energy consumption)</td>
<td>G3, R2, A1, L2, OC</td>
<td>SO(19), PG(19), CF(19), LC(19), LB(18)</td>
<td>282.5</td>
</tr>
<tr>
<td></td>
<td>min PEC</td>
<td>G1, R4, A1, L4, OC</td>
<td>SO(19), PG(19), CF(19), LC(19), LB(18)</td>
<td>243.3</td>
</tr>
<tr>
<td></td>
<td>min DH</td>
<td>G1, R4, A1, L1, OC</td>
<td>SO(22), PG(21), CF(21), LC(22), LB(20)</td>
<td>284.0</td>
</tr>
<tr>
<td>C2</td>
<td>global-optimal solution</td>
<td>G1, R4, A1, L2, OC</td>
<td>SO(22), PG(19), CF(19), LC(19), LB(18)</td>
<td>354.7</td>
</tr>
<tr>
<td></td>
<td>min NPV (cost-optimal energy consumption)</td>
<td>G3, R2, A1, L2, OC</td>
<td>SO(19), PG(19), CF(19), LC(19), LB(18)</td>
<td>364.8</td>
</tr>
<tr>
<td></td>
<td>min PEC</td>
<td>G1, R3, A1, L4, OC</td>
<td>SO(19), PG(19), CF(19), LC(19), LB(18)</td>
<td>325.8</td>
</tr>
<tr>
<td></td>
<td>min DH</td>
<td>G1, R4, A1, L1, OC</td>
<td>SO(22), PG(22), CF(20), LC(22), LB(18)</td>
<td>362.1</td>
</tr>
</tbody>
</table>

* Percentage reduction in primary energy consumption compared to the calibrated base model
* Percentage reduction in discomfort hours compared to the calibrated base model
* Net present value is in terms of 2020 value
Chapter 6. Assessing evidence-based single-step and staged deep-retrofit towards nearly zero-energy buildings (nZEB) using multi-objective optimisation

The analysis of results from the different scenarios evaluated through the developed framework would assist in taking right decisions that fit the criteria in a specific project. They also allow reflecting on the actual decisions that were taken initially in 2005 for the retrofit of the case study building. The results also provided an insight into the economic investments and savings that can be obtained to achieve performance-oriented goals and deep-retrofit of existing buildings in a single-step or multi-stages.

From the first scenario results it can be deduced that if the partial-retrofit was not conducted, deep-retrofit would have cost of €548/m² in 2005 to achieve cost-optimal ZEB performance in a single-step in 2020. However, if the retrofit was planned as the original strategy then €572/m² (in two-stages) would have been required in 2005, but it would not have achieved nZEB performance. However, for the third scenario overlooking the previous retrofit interventions and costs in calculations deep-retrofit would incur an investment of €332/m² (in 2005 value) or €500/m² (including operational costs from 2005-2020). Thus, it can be said from these findings that a single-step retrofit was better in the long-run in terms of achieving nZEB performance and improved comfort with slightly lower costs compared to a two-stage retrofit as assessed in 2005.

From the results of scenario I, an investment of €634,500 (€591/m²) is required in 2020 for the complete deep-retrofit of the building to achieve the cost-optimal nZEB performance. Based on scenario III, a complete retrofit of the existing partial-retrofit building in 2020 would incur an investment of €554,600 (€517/m²) if the existing wall insulation is not replaced. These two solutions offer a promising solution to the current situation of the building.

With respect to achieving greater thermal comfort, global-optimal solutions were better than ‘min PEC’ and ‘min NPV’ solutions for all the scenarios and incurred slightly higher costs, but are worth considering during decision-making. According to the analysis of all the scenarios, it is recommended to opt for renewable solar PV installation along with other selected retrofit measures when aiming for the nZEB performance levels and cost-effectiveness. Typically, the base load in university buildings comprise high plug loads compared to residential building. Thus, taking them into account while planning deep-retrofit intervention is recommended so that the PV systems can be sized accordingly. From the cost-optimal energy consumption solutions of all the three scenarios for the case-study building built in 1975, the proposed nZEB performance levels do not match with the whole building cost-optimal energy consumption of
124 kWh/m²/yr outlined for naturally ventilated buildings under ‘major renovation’ in Part-L. Thus, highlighting the need for evidence-based studies in the Irish context. Ireland may face substantial fines of up to €600 million for missing the European carbon reduction targets of 2020 [64]. With MVHR included as a retrofit measure, all the scenarios highlighted the maximum reduction in DH and a significant improvement in IAQ compared to other solutions without MVHR. The MVHR along with other retrofit measures was proposed to improve the thermal comfort and indoor air quality in offices and lecture rooms based on previous IEQ study results [44]. The improvement of IEQ through deep-retrofits could be taken into account into economic costs by increasing work productivity [65]. Otherwise, the addition of MVHR is not a cost-effective measure for this case study, especially when integrated with existing heating system. But for university buildings, it can be considered as an important deep-retrofit measure irrespective of the high economic investments for improved health benefits and increased productivity.

6.7 Conclusions

The paper presented a methodological framework with three scenarios applied to an existing partially-retrofitted university building built in 1975 to test the cost-effectiveness of single-step and staged deep-retrofits towards achieving nZEB performance. Generally, the number of solutions that are potentially feasible are very high in retrofitting. However, multi-objective optimisation offers a focused outlook on the best set of retrofit measures. The use of multi-objective optimisation by coupling jEPlus+EA and EnergyPlus brought robustness in search of the optimal retrofit measures by exploring a large search space. The measures investigated for deep-retrofit showed the possibility to achieve the nZEB performance level along with improved comfort and cost-optimality. This research used a calibrated and validated model from the previous study by the authors for the simulation of scenarios to evaluate the single-step and staged retrofit approach. The global-optimal solutions were obtained by selection of closest solution on the Pareto front to utopia point from multi-objective optimisation results. Other solutions also focused on single objectives i.e. minimisation of NPV/ DH/ PEC. The decision-maker will be able to select the solution that meets the requirements and satisfies the budget constraints. To achieve larger energy reductions, the paper focused on including measures related to controls that included setpoint adjustments within a defined range and presented a very feasible intervention economically. Growing demand for healthy buildings, yet delivering high energy performance, is challenging for existing buildings. Thus, the
inclusion of MVHR was also tested for improvement of indoor air quality. The focus of the work was also to incorporate the assessment of indoor comfort while optimising for cost and energy; therefore, the three-objective optimisation involved primary energy consumption (PEC), discomfort hours (DH) and net present value (NPV) that presented several deep-retrofit solution packages.

It is difficult to generalise the conclusions for other non-domestic buildings; however, this study presents crucial findings that outline the achievable cost-optimal nZEB performance in Irish conditions for a university building of a specific genre. Scenario I and III with deep-retrofit solutions completed in a single-step resulted in achievable energy performance in the range of approximately 75 - 90 kWh/m²/yr (~58 – 71 kWh/m²/yr without plug loads) with maximum investment of 591€/m² and €517/m² in 2020, respectively. Whereas, in scenario II deep-retrofit on the partially retrofitted building achieved energy performance in the range of approximately 92 – 100 kWh/m²/yr (~75 – 80 kWh/m²/yr without plug loads with an investment of maximum €457/m²). Thus, staged-retrofits would not be able to achieve better or nZEB performance. These findings confirm the achievable cost-optimal nZEB performance level within the range of approximately 75 – 90 kWh/m²/yr for the existing university building. Also, single-step deep-retrofit reduced the energy consumption significantly by 60% and discomfort levels up to 38% compared to the two-stage deep-retrofit. Therefore, it can be concluded that single-step retrofits are better in terms of cost, energy and comfort due to integrated nature of retrofit measures avoiding issues such as end of service-life, redundant building systems and technology compared to staged-retrofits. A significant improvement was also observed in the solutions with MVHR; however, these solutions were not cost-effective. Absence of motivation or financial support for IEQ improvement is a barrier in this regard. Addition of PV and the availability of grants reduced the costs through a reduction in operational costs and investment costs, making it very cost-effective in combination with other retrofit measures. The addition of plug-loads to PEC ascertained the evaluation of overall energy consumption in the analysis and sizing of PV system.

The findings also highlight that the initial decision to partial-retrofit the original building in 2005 did not significantly improve the energy performance, comfort and indoor air quality. And, if the deep-retrofit planned in 2020 considers previous interventions then it would not be able to achieve cost-optimal nZEB performance.
This research adds to the ongoing debate on long-term renovation strategies and their feasibility by presenting an evidence-based study outlining the impacts of decision making for single-step and staged-retrofit and achievable performance benchmarks for university buildings that may entail them. The presented research also aims to add to the database of studies on deep-retrofit of university buildings in Ireland and be an exemplar for promoting the nZEB approach.

### 6.8 References


Chapter 6. Assessing evidence-based single-step and staged deep-retrofit towards nearly zero-energy buildings (nZEB) using multi-objective optimisation


Chapter 6. Assessing evidence-based single-step and staged deep-retrofit towards nearly zero-energy buildings (nZEB) using multi-objective optimisation


Chapter 7: Conclusions and future work
7.1 Chapter overview

This chapter presents the thesis conclusions and future work. The main chapters of the thesis are structured by four journal publications from Chapter 3 to Chapter 6, focusing on the individual objectives of the thesis. The overall conclusions of this work and their applicability in the current scenario are discussed, while giving a direction to the retrofit industry in Section 7.2. The scope of future work and possible directions are outlined in Section 7.3. Finally, the practical implications of this research are presented in Section 7.4 on a broader level.

7.2 Discussion and conclusions

Chapter 1 of the thesis described the energy consumption trends in the European Union, energy efficiency policies related to buildings, building renovation scenarios and definitions for nZEB set out by the EU member states. Overall, the motivation for conducting this research was presented and how it aims to contribute to the existing scenario of nZEBs for existing non-domestic buildings. Further, the research relevance was presented, and a comprehensive research framework was outlined for the thesis. The methodology of the thesis was prepared based on the findings of the scoping study presented in Chapter 2 and Chapter 3.

In Chapter 2, an extensive literature review was presented focusing on the state of the art applied in this research. It assisted in identifying major gaps in theory to be addressed and considered in this research. There is ample evidence in the literature on the impact of better IEQ on occupants and their productivity. It is estimated to have an impact on productivity from 0.5 to 9% due to indoor air temperature, ventilation and IAQ. However, quantification of productivity still requires common indexes to be considered in the financial decision-making of the retrofit projects. Giving importance to IEQ is the key to achieving healthy buildings while planning for deep-retrofits aimed at achieving nZEB performance. Current retrofit approaches are more energy centric, but they need to refocus on IEQ due to its high intangible benefits. The findings in Chapter 6, illustrates that it is possible to improve thermal comfort and IAQ significantly while aiming for high energy performance and reduced costs in deep-retrofits. More case studies are required to substantiate this finding for different climate zones of Europe and identify the thresholds for other existing buildings.

Due to the complex interaction in the supply chain of the retrofit industry, stakeholder consultation, workshops, charrettes and meetings can assist to filter the issues and create
awareness about them. These industry engagement methods and techniques add value to the research and provide new knowledge that is difficult to acquire only through literature. From the findings of the stakeholder investigation in Chapter 3, several barriers, gaps and challenges were identified in the retrofit industry in Ireland. These were in technical (e.g. low-quality auditing, variation in measured and actual performance), environmental (e.g. low preference to IEQ and health impacts) and industrial (e.g. lack of experts, lack of decision-making and solutions for non-domestic buildings) categories. Also, many legislative (e.g. lack of regulations and standards), social (e.g. lack of awareness on benefits of retrofits) and economic issues (e.g. high upfront costs, the imbalance between retrofit building typology) were identified. Although, many findings were similar to the issues existing in other EU member states, the Irish stakeholders’ perspective reinforced and highlighted the requirement of solutions for some of them through this research. The dearth of case-studies on non-domestic retrofits, their diagnosis, monitoring, energy and IEQ performance were also major gaps observed in the Irish context which are required to be dealt within the industry to accelerate the rate of renovation and raise awareness. nZEB energy performance benchmarks were not found to be rigorously defined for non-domestic buildings compared to domestic buildings in Ireland. Furthermore, there were conflicting opinions on nZEB goals, especially with respect to the variables of indoor comfort, air-quality, cost effectiveness and energy performance. The studied market trends also indicated that existing non-domestic buildings faced bigger challenges compared to domestic buildings due to the absence of decision-making tools and methods. Many of these findings could also be extended to other member states for further investigation.

In order to provide guidance to the retrofit industry for conducting a standard based assessment of existing buildings, a field study of university building was conducted in Chapter 4. The focus of the field-study was to understand the implications of retrofits on IEQ. Short-term and long-term measurements gave adequate information for analysis of major issues in the existing building. However, these were time consuming and may deter ones willingness to conduct them. Occupant surveys provide detailed information on their satisfaction, operation and usage of the building systems and it is not possible to capture these only by technical methods. It is advised to carry out detailed occupant surveys before planning the retrofit strategies. The standards such as EN15251 classify expected level of comfort into different categories of buildings, yet it is still not thoroughly developed in its applicability to post-war buildings (>35 yrs. old) for its assessment. Results in Chapter 4 highlight that in temperate-oceanic climate there are a different level of thermal expectations in contrast to those mentioned for existing buildings in
the standard. The occupants were satisfied with slightly-cool temperatures with low-clothing insulation reflecting a strong role of social and behavioural influence in comfort expectations. Overheating issues were also noted in a few zones during the Spring due to uncontrolled heating and lack of mechanical ventilation. The use of CO₂ measurements and decay rate methods for assessment of IAQ in offices and lecture rooms of the field study gave crucial insights into the lack of fresh air and ventilation during winters. It also determined poor IAQ in lecture rooms due to high occupancy and lack of appropriate measures for ventilation.

Compared to new buildings, old buildings require careful investigation and standard guidelines for their assessment before deep-reetrofit especially in case of protected buildings. There is an absence of such guidelines that are accessible to the industry and thus limits their capabilities and motivation. The current process of retrofitting lacks essential focus on methods to identify problems and address them in an integrated way, and this has been observed in the findings from Chapter 3. A proper understanding of the diagnosis and intervention principles can improve the overall cognizance of the deep-retrofits. Several measurement and inspection techniques such as the blower door test, tracer gas test, thermal imaging, and thermofluxometry can give detailed insights into issues such as air-leakage, thermal bridging and dampness etc that can influence decision making with respect to retrofitting. These aspects must be explicitly considered during the planning of retrofits and used to inform robust building energy models that can be effective in assessing the overall impact of potential retrofit solutions on the building’s performance. Existing non-domestic buildings pose challenges in retrofit due to variable occupancy patterns, lack of personal control over thermal comfort and ventilation, outdated building structures and redundant building systems. An important aspect to be considered during measurement and data collection is the resolution of data e.g. minute/hourly/daily time-step based on the analysis and further use, as these affect the analysis of data and calibration of building energy models significantly. Findings from Chapter 4 and 5 also elaborate that the effect of partial/ad-hoc/shallow retrofits was not significant in terms of improving energy efficiency and comfort. Therefore, it can be deduced that investment decisions should be carefully planned and avoid such retrofit decisions that entail very few benefits.

Building energy models are being increasingly used for analysing the impact of retrofit interventions. However, there are no standard protocols to develop such models which affect their usage and reliability for IEQ based studies other than energy. The relevance of calibrated
building energy models is discussed in Chapter 2. Lack of literature was observed on modelling old buildings (30-50 yrs.) that have high uncertainties in inputs. In Chapter 5, the proposed automated-calibration methodology reduced the uncertainties and helped in developing a robust model using different tools and techniques for the post-war university building. The calibration was conducted using energy consumption and indoor environmental data making it suitable for IEQ and energy-based evaluation for different retrofit interventions. The acceptance criteria were only just met for the energy and indoor air temperature. Therefore, the results showed that achieving calibration was difficult for the field study building due to existing uncertainties in building construction and operation. Although, the use of the Morris method for sensitivity analysis gave better insights into the selection of calibration parameters and prioritising them, the application of other global methods may further improve the calibration results. Based on the findings from Chapter 5, it can be said that it is important to conduct detailed assessment of existing buildings, use occupant modelling methods and consider plug-loads in simulation models to increase their reliability and achieve better calibration results. It can also be concluded that automated-calibration approach may be preferred over a manual-iterative approach, as it allowed a large parameter set to be altered simultaneously saving modelling time and cost in this work.

Retrofit measures are often not integrated in the industry practices, thus reducing the potential of achieving higher benefits. Literature in Chapter 2 highlighted how different retrofit measures can be combined but it lacks evidence on the impact of partial or deep retrofits on IEQ. Without simulations models, it is not possible to understand the overall impact of retrofit measures accurately. Therefore, it is important to combine the retrofit solutions and analyse them for their coherent performance. Based on the issues identified in Chapter 4, the proposed retrofit measures in Chapter 6 included envelope, operation and control, load reduction measures and renewable energy systems. Envelope based measures were cost intensive compared to setpoint adjustments that were very cost-effective. Both the measures were responsible for significant reduction in energy demand and improvement of IEQ which corresponds to the findings from the sensitivity analysis in Chapter 5. Chapter 6 of the thesis provided an approach where the deep-retrofit packages were studied on the calibrated building energy model using multi-objective optimisation (MOO). Use of MOO significantly reduced the time required to run the integrated analysis on retrofit measures and find the best solutions. However, existing simulation tools still need to further develop to make the process easier for the industry and reduce the issues of interoperability, data management and analysis. Feasibility
of achieving cost-optimal nZEB performance for the field study building depended largely on the support of grants for the retrofit construction investment costs and solar PV. Higher incentives and financial support for renewable energy systems can offset the energy demand of existing non-domestic buildings. Legislation and policies across the EU have focused upon financing the energy aspects and there is very little-known motivation or support for improvement of IEQ in buildings financially. As outlined in the results of Chapter 6, the use of MVHR in lecture rooms was very effective in managing the CO₂ levels and efficient heat recovery after retrofit measures were applied. However, the absence of any incentive for these systems make them cost-ineffective and absent during decision-making. Discussion in Chapter 2 showcased that the improvements to IEQ render huge savings in terms of productivity and performance of occupants. The renovation policies in the EU need to consider these aspects parallel to energy efficiency measures for the provision of healthy buildings.

Focus on long-term renovation policies (15-20 yrs.) by the EU might prove to be an effective step in dealing with the existing non-domestic building stock. However, findings from Chapter 6 provides evidence from the analysis of deep-retrofit packages for the field study building that single-step or staged retrofit approaches for long-term may not equally result in cost-optimal nZEBs. A single-step approach was responsible for up to 60% reduction in energy and 38% in discomfort hours compared to the base model. However, staged-retrofit were only €60/m² less than single-step and gave reduction of up to 39% in energy and 19% in discomfort hours. Therefore, it can be concluded that, single-step retrofit performs better in terms of cost, energy and comfort due to the integrated nature of retrofit measures and avoidance of problems such as the end of service-life, redundant building systems and technology that may not work in future with further stages of retrofit. In staged-retrofit, these issues limit the complete benefit of achieving nZEB performance and better IEQ. It is, therefore, possible to deep-retrofit existing field study building and achieve nZEB performance with improved IEQ using adequate financial support. Since these findings are only for one typology of non-domestic building, further case-studies are required in different member states to completely understand the validity of long-term renovation strategies. This would be an essential step to guide stakeholders in decision-making for deep- retrofits.
Chapter 7. Conclusions and future work

7.3 Future work and directions

The research work presented in this thesis presented many new challenges and opportunities to conduct further research and investigate their implications in achieving nZEBs and to improve the built-environment. This section presents some of the directions where future research can be conducted to improve its impact.

7.3.1 Data collection and analysis

This research required an extensive collection and analysis of data in different forms and for different purposes. It was acquired for pre/post-processing during stakeholder investigations, indoor environmental quality assessment, building energy model development, and calibration. In Chapter 3, a major area for future interventions identified was to develop methods that encourage occupant participation in surveys, workshop and interviews for studies that involve stakeholder investigation and is recognised as one of the major barriers in such research. Also, there were many challenges regarding privacy during surveys and data collection through sensors that also require appropriate solutions to make the process more reliable and acceptable. In Chapter 4, point-in-time surveys were conducted, measurements for indoor environment and other audit measurements were carried out. One of the main concerns while developing the data collection campaigns for the field study was the organisation and need of the different types of measured data and their impact on several aspects of the retrofit studies (eg. specific type and resolution of data required to analyse shallow, medium or deep retrofit). However, the scale and impact of data required for such a retrofit study were not outlined or standardised elsewhere which presents a gap and is required to be studied to reduce the time and effort that is required for such assessment studies. A data-management model may also be developed for retrofit based studies by comprehensive analysis of data requirements for specific purposes in retrofit projects and its acquisition requirements with appropriate scientific techniques and methods.

7.3.2 Occupant behaviour and productivity

Studies are required for integrating IEQ standards with energy performance in retrofits, specifically focusing on achieving nZEBs for existing buildings. Evaluation of productivity benefits requires further research in relation to nZEBs as this area is understudied and undermines the complete merit of deep-retrofits.
Chapter 7. Conclusions and future work

The issues that emerged regarding these aspects include:

- developing methods that incorporate occupant interaction and behaviour (e.g. opening of windows and doors) regulating impact on simulation models through occupant modelling to minimise the uncertainty and reduction of the performance gap.

- establish commonly accepted index/metrics and methodologies for assessing the retrofit impact on occupant health and productivity through quantification of benefits and its assessment.

The productivity indexes/metrics can also be considered to become a part of post-retrofit building certification standards or Energy Performance Certificates (EPCs). It was infeasible to address these aspects within the scope of this research. Therefore, the future research goal of the author is to work further on understanding the occupant’s role and dynamics regarding the performance of nZEBs.

7.3.3 Building energy model, calibration and optimisation

The building energy model for the field study building was developed in Chapter 5 using state-of-art modelling and simulation tools. Integration of building model, energy modelling and optimisation specially for retrofit planning presented an opportunity to work on the development of tools that specifically address the workflow or interoperability required to reduce the effort and time. The calibration methodology could be further developed to identify the number of stages and criteria required for the specific type of application of energy models such as thermal comfort, acoustic comfort, visual comfort and indoor air quality. The results in Chapter 6 were presented based on tri-objective optimisation. The solutions can also be explored based on more than three objectives with assigned weightage to each objective.

Some future research directions and areas that were identified include:

- The building energy models require intensive work and a range of input data; however, models could be developed through a reduced order modelling (ROM) approach wherein the model is based on statistically fewer complex relationships and inputs as compared to the transient models built through traditional building energy simulation tools.
• The uncertainty analysis was conducted using the Morris method; however, application of other global uncertainty methods could be explored such as regression, variance-based and meta model for accurate analysis.
• The building energy model was calibrated using GA optimisation where inputs for analysis such as population, crossover rate, mutation rate and generation must be defined. Further research can be conducted for statistically determining the optimal values for these inputs as they affect the time, accuracy and search for optimal solutions in pareto fronts generated by them.

7.3.4 Retrofit strategies
Several opportunities were identified for the development of retrofit strategies that need to be addressed. Deep retrofits can succeed only when the retrofit measures are integrated, and their performance is evaluated correctly before execution in the projects. To assist this approach following points may be useful in achieving the right solutions.

• development of the integrated building envelope retrofit design strategies, e.g. building integrated photovoltaics can be developed for retrofit to improve the envelope design addressing energy-efficiency, thermal and airtightness issues through one solution.
• evaluation of hybrid MVHR in different climatic zones for their effectiveness with natural ventilation.
• development of retrofit tool-kits for existing non-domestic buildings based on different typologies.

There is a lack of evidence in the literature to support long-term renovation strategies or building passports and their actual benefits are not well outlined for non-domestic buildings and this is a gap that is required to be studied. This research was able to address this aspect very briefly. However, in-depth case-studies and their financial evaluation would be required to strengthen uptake for large-scale deep-retrofits especially for non-domestic buildings.

7.4 Practical implications of research
It is estimated that approximately 109,900 people are employed in the construction industry in Ireland and approximately 1,000,000 Irish homes and 130,000 non-domestic units require
retrofitting by 2020\(^1\). This is a huge opportunity to improve the building stock, but there are many issues that require clear attention to achieve national goals. One of the major contributions from this research is the identification of attitudes and approach of Irish retrofit industry professionals towards achieving nZEBs as barriers, gaps and challenges. These results could guide the policy makers and the industry in seeking right solutions so that the opportunities can be created, the supply chain can be strengthened, awareness can be raised, and rate of renovation can be accelerated.

The estimated total energy spend across the public sector was €536 million in Ireland in 2016\(^2\). Educational buildings consumed nearly 857 GWh of primary energy and 316 GWh (27% over baseline of 2009 i.e. 1173 GWh) was saved during 2016 by these buildings through different retrofit measures\(^3\). The National Energy Efficiency Action Plan intends to achieve a reduction of 33% in the public sector energy consumption by 2020 in Ireland. Half of the buildings in the public sector are educational buildings, the majority being primary schools\(^4\). Approximately 1000 buildings belong to third-level institutions (approx. 50 institutions in Ireland).

Educational buildings (excluding Schools and Education training buildings) spent approximately €40 million on energy consumption in 2016. Assuming an average energy intensity for educational buildings of 190 kWh/m\(^2\)/yr, then, according to the nZEB levels proposed through deep-retrofit (75 kWh/m\(^2\)/yr) in this research another 518 GWh can be saved by these buildings (achieving 44% of reduction over baseline), saving €24 million and 111,000 tonnes of CO\(_2\) emissions. To deep-retrofit, these existing buildings to nZEB, a capital cost of €2.7 billion (assuming an investment of €591/m\(^2\)) would be required for 30 years. This amount is relatively very small compared to the €35 billion\(^5\) required to retrofit residential buildings as estimated by Sustainable Energy Authority of Ireland (SEAI) in 2017. These findings may be considered in the national renovation roadmap and used assessment of the overall impact of retrofitting existing educational buildings to nZEBs.

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\(^3\) Ibid


\(^5\) Ibid
Chapter 7. Conclusions and future work

Based on the literature review and findings of this research deep-retrofit are assumed to have an impact on productivity due to better IEQ. The increase in productivity is assumed to increase by 1.5% (refer Chapter 2) per occupant. An analysis of the average annual salaries of the full-time employees and students (from the field-study building in this research) would cost approximately €1,032,000 per year to the university. Therefore, a sum of €15,480 can be saved annually based on improvement in each employee performance. This amount, if calculated for the period of deep-retrofit (e.g. 15 years) without considering the time value of money then it would save €232,200 over 15 years and can be counter adjusted in the initial investment costs. This is a major saving and can be considered while deep-retrofit is being planned for the existing non-domestic building. The possibility of financial gains through improvement of productivity can form a strong basis to offset the initial investment costs in deep-retrofits. The author intends to conduct further research and integrate the impact of productivity in deep-retrofit evaluation as highlighted in future work and directions.
Appendix A. Stakeholder surveys

A.1 Cover letter

Dear survey participant;

Purpose of the study:
This study is being conducted by Sheikh Zuhaib (PhD student) of the Dept. of Civil Engineering, National University of Ireland, Galway in order to better understand the current situation of energy efficient retrofits of the existing building stock in Ireland through the experiences of the construction Industry professionals. This research will guide in innovation of technologies and solutions for the retrofit in achieving near zero-energy buildings. In the next 6 months, I plan to publish/disseminate results of this study that focus on existing retrofit practices based on the data provided by the respondents.

Description of the survey procedure and approximate duration of the study:
I would greatly appreciate your completing the survey by clicking on the link below.
http://goo.gl/forms/nuHvdI1Im
Since the validity of the results depend on obtaining a high response rate, your participation is crucial to the success of this study. The data shall be recorded online which will focus on professional practice for achieving energy efficiency in retrofit projects and this will take approximately 6 months to complete.

Description of how confidentiality will be assured and limits to these assurances, if any.
Your response to the survey questionnaire indicates your consent to participate in this study. Please be assured that your responses will be held in the strictest confidence and no personal or professional information will be distributed. As soon as I receive your response, I will get notified by online system. All the responses will be stored for 6 months duration online and will be offline after the data is recorded. If the results of this study were to be written for publication, no identifying information will be used.

Anticipated benefits resulting from this study:
The potential benefits to you from participating in the study are; the major professional practice concerns regarding retrofit of the buildings, general methods useful for building retrofits, efficient technologies and solutions in use by construction industry professionals. The study may be helpful to increase your understanding of the near zero-energy buildings.

The potential benefit to Ireland that may result from this study is the implementation of the EU Energy Performance of Building Directive (EPBD) for achieving near zero-energy building targets by 2020. The respondents will have the opportunity and an option to receive feedback regarding the study results by providing their contact information in the survey form.

Contact information:
If you have any questions about this study, you can contact the person(s) below:
Sheikh Zuhaib
Doctoral Researcher

Dr. Jamie Goggins
Senior Lecturer (Supervisor)
Informatics Research Unit for Sustainable Engineering (IRUSE)
College of Informatics and Engineering, National University of Ireland, Galway.
Appendix A. Stakeholder surveys

A.2 Survey questionnaire

n-ZEB Retrofit project questionnaire

The purpose of this survey is to gather data on your views and experiences on energy efficient building retrofit projects, technologies and systems for buildings. This questionnaire is directed to the all professionals in the building construction industry, who are associated in some way with any building retrofit project(s).

The information collected is for research and teaching purposes only. Participation in this research is entirely voluntary and respondent's anonymity is assured.

* Required

General Information

1. What is your profession? *
   Mark only one oval.
   - Architect
   - Building surveyor/ engineer
   - BER Assessor/ Energy consultant
   - Construction Manager
   - Civil Engineer/ Structural Engineer
   - Contractor
   - Energy engineer/ manager
   - Quantity Surveyor/ Cost Consultant
   - Researcher
   - Other: ____________________________________________

2. Gender: *
   Mark only one oval.
   - Male
   - Female
   - Transgender

3. What is your age group? *
   Mark only one oval.
   - 18-22
   - 23-28
   - 29-33
   - 34-40
   - 41-50
   - 51-60
   - 61-70
   - 70+

4. What position do you have at your place of work? *
   Mark only one oval.
   - Director (CEO)
   - Associate
   - Senior employee
   - Junior employee
   - Self employed
   - Other: ____________________________________________
Appendix A. Stakeholder surveys

5. **How many building retrofit projects have you worked on?**
   check all that apply
   *Mark only one oval per row.*

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</table>

6. **Please state the locations of the retrofit project(s) that you have been involved in?** *
   check all that apply
   *Check all that apply.

   - [ ] Dublin
   - [ ] Rest of Leinster
   - [ ] Connacht
   - [ ] Munster
   - [ ] Ulster (excluding Northern Ireland)
   - [ ] Northern Ireland
   - [ ] England
   - [ ] Wales
   - [ ] Scotland
   - [ ] Rest of Europe
   - [ ] Rest of World

7. **Select the typical purpose(s) of building retrofit you followed in the project(s)?** *
   check all that apply
   *Check all that apply.

   - [ ] Acoustical comfort
   - [ ] Code compliance
   - [ ] Change of building use (or part of)
   - [ ] Energy and cost savings
   - [ ] Failure remediation (air, water infiltration, material etc.)
   - [ ] Improved air quality and better lighting
   - [ ] Renovation (image update)
   - [ ] Thermal comfort
   - [ ] Other:  ___________________________________________
Appendix A. Stakeholder surveys

8. What was the typical duration of construction of the retrofit project(s) in each category mentioned below? check all that apply. Mark only one oval per row.

<table>
<thead>
<tr>
<th>Building Type</th>
<th>1-6 months</th>
<th>7-12 months</th>
<th>13-24 months</th>
<th>25-36 months</th>
<th>37 months or more</th>
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</table>

9. What degree of involvement(s) did you have in the retrofit project(s)? *
Check all that apply.

☐ Decision level
☐ Detail level
☐ Supervision level
☐ Planning level
☐ Participation level
☐ Other: ________________________________

Methods adopted

10. Which professionals was (were) involved in the domestic retrofit project(s)? *
Check all that apply.

☐ Architects
☐ Building occupants/users
☐ Building Owners
☐ Building services engineers
☐ Civil Engineers
☐ Contractors
☐ Electrical Engineers
☐ Financers
☐ Facility managers
☐ Housing associations
☐ Local authorities
☐ Mechanical Engineers
☐ NGO's
☐ Quantity surveyor/ cost consultant
☐ Technology manufacturers
☐ Not applicable
☐ Other: _____________________________________________
Appendix A. Stakeholder surveys

11. Which professionals was (were) involved in the non-domestic retrofit project(s)? *
   Check all that apply.
   - Architects
   - Building occupants/users
   - Building Owners
   - Building services engineers
   - Civil Engineers
   - Contractors
   - Electrical Engineers
   - Financers
   - Facility managers
   - Housing associations
   - Local authorities
   - Mechanical Engineers
   - NGO's
   - Quantity surveyor/cost consultant
   - Technology manufacturers
   - Not applicable
   - Other: ______________________________________________________

12. Which of the following typically affected the choice of retrofit strategies? *
    Check all that apply.
    - Availability of solutions or technology
    - Cost involved
    - Previous personal experience with solution or technology
    - Proven solutions or technology
    - Stakeholder pressure
    - Time
    - don't know
    - Other: ______________________________________________________

13. Which of the following site audit procedures were performed before the retrofit(s)? *
    Check all that apply.
    - Air-tightness test
    - False smoke
    - Heat flow meters
    - Thermography
    - Tracer gas
    - Visual inspection
    - none
    - don't know
    - Other: ______________________________________________________
Appendix A. Stakeholder surveys

14. Did you follow any regulations/standards/rating method concerning the retrofit of domestic buildings? *
   Check all that apply.
   □ BER
   □ BREEAM
   □ General Building Regulations
   □ LEED
   □ NSAI
   □ Passivhaus standard
   □ None
   □ Other: ........................................................................

15. Did you follow any regulations/standards/rating method concerning the retrofit of non-domestic buildings? *
   Check all that apply.
   □ BER
   □ BREEAM
   □ General Building Regulations
   □ LEED
   □ NSAI
   □ Passivhaus standard
   □ None
   □ Other: ........................................................................

Technology and Solutions

16. Please rate the requirement of following analysis tools in order of your preference for the retrofit planning.
   Mark only one oval per row.

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<tr>
<th>Tool</th>
<th>not important</th>
<th>somewhat important</th>
<th>important</th>
<th>very important</th>
<th>not sure/not applicable</th>
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17. What type of facades have you retrofitted? *
   Check all that apply.
   □ Masonry (Single leaf)
   □ Masonry cavity wall
   □ Precast concrete
   □ Curtain wall (less than 50% glass)
   □ Highly glazed (greater than 50% glass)
   □ Timber
   □ Concrete block masonry
   □ None
   □ Other: ........................................................................
Appendix A. Stakeholder surveys

18. Which upgrade retrofit technologies or systems were available with difficulty during project(s)?

* Check all that apply.

- Acoustical insulation
- Building Energy Management Systems
- Cold bridging systems
- Doors
- Electrical and lighting systems
- HVAC systems
- Hot-water systems
- Prefabricated structural systems
- Rain or water barrier systems
- Sensor based control systems
- Shading systems
- Solar based technology
- Thermal insulation
- Windows
- Don't know
- Other: ____________________________________________________________

19. Which retrofit technologies/systems were not cost-effective?

Comment below.

____________________________________________________________________

____________________________________________________________________

____________________________________________________________________

Implementation and Performance

20. How do you rate the typical energy performance of the building(s) pre-retrofit as per BER?

(omit if required)

Mark only one oval per row.

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Appendix A. Stakeholder surveys

21. How do you rate the typical energy performance of the building(s) post-retrofit as per BER?
   (omit if required)
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<tr>
<td>Apartment- Top-floor</td>
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<tr>
<td>House- End of terrace</td>
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<td>House- Mid-terrace</td>
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<td>House- Semi-detached</td>
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<td>House- Detached</td>
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<tr>
<td>Commercial building (retail)</td>
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<tr>
<td>Educational (school, college, university)</td>
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<tr>
<td>Other Public buildings (library, museum, gov. buildings, etc.)</td>
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<td>Office building</td>
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<td>Mixed-use building</td>
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<td>Leisure (sports, gym etc.)</td>
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<td>Others</td>
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</tbody>
</table>

22. How often the building occupants/owners/users were involved in decision making?
   Mark only one oval per row.

   never  once  sometimes  frequently  everytime

| Occupants (residents etc.) |    |    |    |    |    |
| Users (employee etc.)      |    |    |    |    |    |
| Owners                     |    |    |    |    |    |

23. Select the issues and rate the difficulty levels you faced during the retrofit project(s)
   Mark only one oval per row.

<table>
<thead>
<tr>
<th></th>
<th>very easy</th>
<th>easy</th>
<th>average</th>
<th>difficult</th>
<th>very difficult</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adaptive technology</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aesthetics</td>
<td></td>
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<tr>
<td>Costs</td>
<td></td>
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<tr>
<td>Component size</td>
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<tr>
<td>Flexibility in use</td>
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<tr>
<td>Installation</td>
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</tr>
<tr>
<td>Operation</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Performance level</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Quality</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Skilled labour</td>
<td></td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>Others</td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

24. Please mention your concerns and needs (if any) specifically related to retrofit technology and systems *

   ........................................................................................................
   ........................................................................................................
   ........................................................................................................

273
Personal Information (Optional)

(If you wish to participate in the further study)

25. Name:

---------------------------------------------------------------------

26. Organisation:

---------------------------------------------------------------------

27. Contact email:

---------------------------------------------------------------------

28. Contact phone:

---------------------------------------------------------------------

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Appendix B. Stakeholder interviews

B.1 Consent form

Project context: “Achieving nearly zero-energy buildings (nZEB’s) through retrofit”

I agree to participate in this project, whose conditions are as follows:

- The aim of this project is to diagnose the retrofitting of building façades. For this purpose, semi-structured interview will be conducted with key informants in the construction industry.

- Each interview will last for less than 60 minutes and questions will deal with energy efficient building façade retrofits, performance and perception of building facades, assessment of the retrofit design methods, construction and technology in Ireland.

- The interview I give and the information it contains will be used solely for the purposes defined by the project.

- At any time, I can refuse to answer certain questions, discuss certain topics or cease to participate in the interview without prejudice to myself.

- The interview will be recorded to make the interviewer’s job easier. However, the recording will be destroyed as soon as it has been transcribed.

- All interview data will be handled so as to protect the confidentiality of sources. Therefore, no names will be mentioned and the information will be coded.

- All data will be kept under lock and key and will be destroyed at the end of the project.

- For information on the project, I can contact Dr. Jamie Goggins (Senior Lecturer)
  Dept. of Civil Engineering, College of Engineering and Informatics, NUI Galway
  E: jamie.goggins@nuigalway.ie

Respondent's signature: ____________________________
Address: _______________________________________
Phone: ____________________________ Date: _____________

Interviewer’s signature: ____________________________ Date: _____________

Person to contact if you have any questions:
Sheikh Zuhaib
Doctoral Researcher, IRUSE, Dept. of Civil Engineering, College of Engineering and Informatics, National University of Ireland, Galway, Ireland
## B.2 Interview structure

<table>
<thead>
<tr>
<th>General Information</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name:</td>
</tr>
<tr>
<td>Profession:</td>
</tr>
<tr>
<td>Address:</td>
</tr>
<tr>
<td>Email:</td>
</tr>
<tr>
<td>Phone:</td>
</tr>
</tbody>
</table>

### Experience on envelope retrofits

#### Descriptive Questions (AND/ OR)

1. Can you tell me about the role of building envelopes in retrofits?
2. What are the existing and future building envelope/ façade system needs?
3. Do you consider envelope retrofits as ‘fundamental infrastructure problem’ in Ireland?
4. What challenges you faced while working with envelope retrofits?
5. In your experience, which problems are the most common problems (external/ internal) in building envelopes?

#### Normative Questions

1. How do you identify their role?
2. What factors affect the decision making for their retrofit?
3. How do you diagnose the problems at first?
4. Does appearance/ aesthetics matter to you and the client?
5. How do you generally deal with the sophistication of existing envelope/ façades?
6. Do you focus on basic metrics of performance like thermal, visual and acoustics together?
7. Where do most problems occur and what is the potential impact?
8. How do you deal with envelope insulation in retrofits?
9. What are the factors through which you quantify the underperformance of envelope/ façade?
10. What measures you adopt to deal with the thermal bridging and air-tightness?
11. How do you measure the energy performance of the façade pre and post retrofit?
12. How do you rectify daylight and ventilation issues?
## Assessment of design, construction and delivery

**Descriptive Questions (AND/ OR)**

1. According to you, what are the governing factors for building envelope façade retrofits?
2. In your opinion, how satisfied are people with the envelope retrofits?
3. How do you assess the implementation of envelope retrofits?
4. Do you think change in geometry or configuration of envelope/ façade makes a difference in energy performance?
5. What is your opinion on the market phenomena?

**Normative Questions**

1. What changes do you make in the envelopes?
   - *Replacement of components / Addition of layers / Addition of components*
2. What envelope/façade construction type do you have expertise in?
3. Do you implement new materials to improve energy performance?
4. Do you consider embodied energy important in retrofits?
5. What passive design methods have you used?
6. Do you perform structural analysis?
7. What building standards you refer in your practice?

## Technology and systems

**Descriptive Questions (AND/ OR)**

1. In your opinion, what technologies should be available for retrofits?
2. What risks do you anticipate in envelope retrofits?

**Normative Questions**

1. How do you consider your approach to be energy efficient?
2. To what extent your base your decisions on cost over energy performance?
3. Do you use any software for design and digital analysis?

## Issues and concerns

1. What are the issues and concerns related to envelope retrofits?
### Appendix C. Field study data collection

#### C.1 Description of data collection strategy

<table>
<thead>
<tr>
<th>Quantities measured, and standards followed</th>
<th>Instrument</th>
<th>Measured parameters</th>
<th>Measurement range</th>
<th>Accuracy</th>
<th>Resolution of data collected</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indoor thermal comfort, air quality and visual comfort (based on ISO 7726 and ASHRAE 55)</td>
<td>Portable measurement Instrument (PMI) - Testo 480</td>
<td>Indoor air temperature</td>
<td>0 to +50 °C</td>
<td>±0.3 °C</td>
<td>Class 1</td>
<td>summer, autumn, winter and spring (Frequency 3 min)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Relative Humidity</td>
<td>0 to 100 %RH</td>
<td>±2 %RH</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mean Radiant Temperature</td>
<td>0 to +120 °C</td>
<td>Class 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>CO₂ concentration</td>
<td>0 to +10000 ppm CO₂</td>
<td>±(75 ppm ±3 % of mv) (0 to +5000 ppm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Light intensity</td>
<td>0 to +100000 Lux</td>
<td>Class C according to DIN 5032-7; f1 = 6% V-Lamda; f2 = 5% cos</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Air velocity</td>
<td>0 to +5 m/s</td>
<td>±0.5°C</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Absolute pressure</td>
<td>+700 to +1100 hPa</td>
<td>±3 hPa</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measurement of indoor parameters (air temperature and RH) based on ISO 7730 and ISO 7726</td>
<td>Lascar (EL-USB-2+) data loggers</td>
<td>Air temperature</td>
<td>-35°C to 80°C</td>
<td>0.45°C typical (5°C to 60°C)</td>
<td>1-year duration (Frequency 10 min)</td>
<td>All zones</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Relative Humidity</td>
<td>0 to 100%RH</td>
<td>2.05%RH typical (10 to 90%RH)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal images of the building façade as per specifications in ISO 6781</td>
<td>FLIR T335 thermal camera</td>
<td>Thermal image (320x240 pixels)</td>
<td>-20°C to 650°C</td>
<td>Thermal sensitivity (&lt;0.045°C at 30°C)</td>
<td>Twice</td>
<td>Outside the building</td>
</tr>
<tr>
<td>Measurement of outdoor parameters</td>
<td>IRUSE Weather station, NUI Galway</td>
<td>Dry bulb air temperature</td>
<td>-39.2 to +60 °C</td>
<td>±0.13°C</td>
<td>1 Minute intervals</td>
<td>Outside the building</td>
</tr>
<tr>
<td>Measurement of acoustical comfort</td>
<td>CE-450 Real time Sound Level Meter</td>
<td>Sound Pressure Level (dB)</td>
<td>0 to 140dB</td>
<td>n/a</td>
<td>10 Minute intervals</td>
<td>Inside the building</td>
</tr>
</tbody>
</table>
Appendix C. Field study data collection

C.2 Field-study images

<table>
<thead>
<tr>
<th>Point-in-time surveys with occupants</th>
</tr>
</thead>
<tbody>
<tr>
<td>Room G.17</td>
</tr>
<tr>
<td>Room G.16</td>
</tr>
<tr>
<td>Room G.18</td>
</tr>
<tr>
<td>Room G.16</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Photos of the field study building from outside</th>
</tr>
</thead>
<tbody>
<tr>
<td>View from North</td>
</tr>
<tr>
<td>View from West</td>
</tr>
<tr>
<td>View from East</td>
</tr>
<tr>
<td>View from East (new and old façade)</td>
</tr>
</tbody>
</table>
Appendix C. Field study data collection

Photos from inside

<table>
<thead>
<tr>
<th>Typical lecture room (retrofitted façade)</th>
<th>Retrofitted façade (G.16)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original façade (G.17)</td>
<td>Retrofitted façade (G.1)</td>
</tr>
</tbody>
</table>

Installed Lascar Temperature/RH sensor in different zones

<table>
<thead>
<tr>
<th>Installed Lascar Temperature/RH sensor in different zones</th>
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<tbody>
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</table>
Appendix D. Point-in-time IEQ surveys

D.1 Occupant survey

<table>
<thead>
<tr>
<th>Question</th>
<th>Rating Options</th>
<th>Instructions</th>
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<tbody>
<tr>
<td>1. Name</td>
<td></td>
<td></td>
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<tr>
<td>2. Occupation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Age</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Gender: ◯ M ○ F</td>
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<td></td>
</tr>
<tr>
<td>5. Weight</td>
<td></td>
<td></td>
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<tr>
<td>6. Height</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7. Room No</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8. How long have you worked in this office?</td>
<td></td>
<td>☐ 1-4 months ☐ 5-8 months ☐ 8-12 months ☐ more than 1 yr.</td>
</tr>
<tr>
<td>9. Are you near an exterior wall (within 2m)?</td>
<td>☐ Yes ☐ No</td>
<td></td>
</tr>
<tr>
<td>10. Are you near a window (within 2m)?</td>
<td>☐ Yes ☐ No</td>
<td></td>
</tr>
<tr>
<td>11. What is your general thermal comfort sensation right now? (Check the one that is most appropriate)</td>
<td></td>
<td>☐ Hot ☐ Warm ☐ Slightly warm ☐ Neutral ☐ Slightly cool ☐ Cool ☐ Cold</td>
</tr>
<tr>
<td>12. Are you satisfied with lighting level at your work desk?</td>
<td>☐ +3 ☐ +2 ☐ +1 ☐ 0 ☐ -1 ☐ -2 ☐ -3</td>
<td>☐ Very satisfied ☐ Very dissatisfied</td>
</tr>
<tr>
<td>13. Are you satisfied with the air quality of your workplace?</td>
<td>☐ +3 ☐ +2 ☐ +1 ☐ 0 ☐ -1 ☐ -2 ☐ -3</td>
<td>☐ Very satisfied ☐ Very dissatisfied</td>
</tr>
<tr>
<td>14. What level of humidity do you feel right now?</td>
<td>☐ Very dry ☐ Moderately dry ☐ Slightly dry ☐ Neutral ☐ Slightly damp ☐ Moderately damp ☐ Very damp</td>
<td></td>
</tr>
<tr>
<td>15. What level of air movement do you feel right now?</td>
<td>☐ +3 ☐ +2 ☐ +1 ☐ 0 ☐ -1 ☐ -2 ☐ -3</td>
<td>Very still Much moving</td>
</tr>
<tr>
<td>16. Are you satisfied with the noise level at your workplace?</td>
<td>☐ +3 ☐ +2 ☐ +1 ☐ 0 ☐ -1 ☐ -2 ☐ -3</td>
<td>☐ Very satisfied ☐ Very dissatisfied</td>
</tr>
<tr>
<td>17. What is your activity level for the past 15 minutes?</td>
<td></td>
<td>☐ Reclining ☐ High activity (lifting/packing)</td>
</tr>
<tr>
<td></td>
<td>☐ Seated, reading ☐ Walking about</td>
<td></td>
</tr>
<tr>
<td></td>
<td>☐ Standing, relaxed ☐ Typing</td>
<td></td>
</tr>
<tr>
<td></td>
<td>☐ Light activity standing ☐ Writing</td>
<td></td>
</tr>
<tr>
<td></td>
<td>☐ Medium activity standing ☐ Eating</td>
<td></td>
</tr>
<tr>
<td>18. What items of clothing are you wearing right now? (Check all that apply)</td>
<td></td>
<td>☐ Short-sleeve shirt/blouse ☐ Dress ☐ Quilted jacket</td>
</tr>
<tr>
<td></td>
<td>☐ Long sleeve shirt/blouse ☐ Shorts ☐ Suit</td>
<td></td>
</tr>
<tr>
<td></td>
<td>☐ T-shirt ☐ Athletic sweatpants ☐ Tights</td>
<td></td>
</tr>
<tr>
<td></td>
<td>☐ Long-sleeve sweatshirt ☐ Trousers/pants ☐ Socks</td>
<td></td>
</tr>
<tr>
<td></td>
<td>☐ Sweater ☐ Undershirt ☐ Boots</td>
<td></td>
</tr>
<tr>
<td></td>
<td>☐ Scarf/cap ☐ Underwear ☐ Shoes</td>
<td></td>
</tr>
<tr>
<td></td>
<td>☐ Jacket ☐ Long sleeve coveralls ☐ Sandals</td>
<td></td>
</tr>
<tr>
<td></td>
<td>☐ Knee-length skirt ☐ Overalls ☐ Slippers</td>
<td></td>
</tr>
<tr>
<td></td>
<td>☐ Ankle-length skirt ☐ Pyjamas</td>
<td></td>
</tr>
<tr>
<td></td>
<td>☐ Other (specify)</td>
<td></td>
</tr>
</tbody>
</table>
Appendix D. Point-in-time IEQ surveys

D.2 Survey at occupant location (by surveyor)

1. Mark the position of the person- 'X', portable heater - 'H', radiator - 'R', computer - 'C', printer - 'P' and other heat sources - 'O'.

2. What is the general layout of your workplace?
   - Private Office
   - Semi-private office (shared)
   - Cubicle with partition (low)
   - Cubicle with partition (high)
   - Open plan (no partition)

3. Occupant distance from the external wall:
   - 0.5m
   - 1.0m
   - 1.5m
   - 2.0m
   - far away

4. Occupant distance from the window:
   - 0.5m
   - 1.0m
   - 1.5m
   - 2.0m
   - far away

5. Current season
   - Spring (March - May)
   - Summer (June - August)
   - Autumn (September - November)
   - Winter (December - February)

6. Current sky conditions:
   - Cloudy
   - Mostly Cloudy, or Considerable Cloudiness
   - Partly Cloudy, or Partly Sunny
   - Mostly Clear, or Mostly Sunny
   - Clear, or Sunny

7. Thermostat setting / TRV setting
   - Thermostat setting
   - TRV setting
   - Other

8. Glazing type:
   - Single pane
   - Double pane
   - Other

9. Control conditions around occupant:
   - Window
   - Curtain/blinds
   - Internal door
   - External door
   - Radiator
   - Portable heater
   - Lights

10. Environmental variables:
    - Outdoor temperature (°C)
    - Room air temperature (°C)
    - Relative Humidity (%)
    - Mean radiant temperature (°C)
    - Air velocity (m/s)
    - CO2 concentration (ppm)
    - Lighting level (Lux)

11. Energy consuming appliances in the room
    - Portable heater
    - Lights
    - Portable fan
    - Computer
    - Printer
    - Electric kettle
    - Other

---

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D.3 Survey at lecture room

1. Name: 
2. Course: 
3. Age: 
4. Gender: □ M □ F 
5. Weight: 
6. Height: 

7. Are you near an exterior wall (within 2m)?
   □ Yes □ No 

8. Are you near a window (within 2m)?
   □ Yes □ No 

9. What is your general thermal comfort sensation right now? (Check the one that is most appropriate)
   □ Hot □ Warm □ Slightly warm □ Neutral □ Slightly cool □ Cool □ Cold 

10. Do you feel comfortable now?
    □ +3 □ +2 □ +1 □ 0 □ -1 □ -2 □ -3 
    ▲ Very comfortable ▼ Very uncomfortable 

11. Are you satisfied with lighting level at your desk?
    □ +3 □ +2 □ +1 □ 0 □ -1 □ -2 □ -3 
    ▲ Very satisfied ▼ Very dissatisfied 

12. Are you satisfied with the air quality of your classroom?
    □ +3 □ +2 □ +1 □ 0 □ -1 □ -2 □ -3 
    ▲ Very satisfied ▼ Very dissatisfied 

13. What level of humidity do you feel right now?
    □ Very dry □ Moderately dry □ Slightly dry □ Neutral □ Slightly damp □ Moderately damp □ Very damp 

14. What level of air movement do you feel right now?
    □ +3 □ +2 □ +1 □ 0 □ -1 □ -2 □ -3 
    Very still Much moving 

15. Are you satisfied with the noise level in your classroom?
    □ +3 □ +2 □ +1 □ 0 □ -1 □ -2 □ -3 
    ▲ Very satisfied ▼ Very dissatisfied 

16. What is your activity level for the past 15 minutes?
    □ Reclining □ Typing □ Seated, reading □ Writing □ Standing, relaxed □ Walking about □ Light activity standing □ Eating □ Medium activity standing 

17. What items of clothing are you wearing right now? (Check all that apply)
    □ Short-sleeve shirt/blouse □ Dress □ Quilted jacket □ Long-sleeve shirt/blouse □ Shorts □ Suit □ T-shirt □ Athletic sweatpants □ Tights □ Long-sleeve sweatshirt □ Trousers/pants □ Socks □ Sweater □ Undershirt □ Boots □ Scarf/cap □ Underwear □ Shoes □ Jacket □ Long-sleeve coveralls □ Sandals □ Knee-length skirt □ Overalls □ Slipper □ Ankle-length skirt □ Pajamas □ Other (specify)............................................................... 

18. What changes did you make in your surroundings during the last one hour?
    □ In/On □ Internal door □ Radiator
    | Window | Internal door | Radiator |
    |-------|--------------|---------|
    | On/Open | ☐ | ☐ | ☐ |
    | Off/Closed | ☐ | ☐ | ☐ |
    | No change | ☐ | ☐ | ☐ |

19. Do you feel local thermal discomfort around any part of your body?
    □ Arms □ Head/Neck □ Back □ Palm □ Feet □ None

20. Any other comments regarding thermal comfort?
## Appendix E. Building energy model inputs

### E.1 Details of schedule inputs in EnergyPlus simulation

<table>
<thead>
<tr>
<th>Schedules</th>
<th>Zones</th>
<th>Unit</th>
<th>Time period</th>
<th>Time-step</th>
<th>Used for</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equipment schedule</td>
<td>Offices, Lecture rooms, Post-graduate rooms, Conference rooms, labs</td>
<td>Fraction (equipment load)</td>
<td>Annual</td>
<td>Hourly</td>
<td>computer, monitor, refrigerator, TV, projector, coffee maker, microwave, copier, laser printer, laptop, toaster, electric kettle</td>
</tr>
<tr>
<td>Occupant schedule</td>
<td>Offices, Lecture rooms, Post-graduate rooms, Conference rooms, labs</td>
<td>Fraction (occupant load)</td>
<td>Annual</td>
<td>Hourly</td>
<td>Students, lecturers, professors</td>
</tr>
<tr>
<td>Lighting schedule</td>
<td>Offices, Lecture rooms, Post-graduate rooms, Conference rooms, labs</td>
<td>Fraction (lighting load)</td>
<td>Annual</td>
<td>Hourly</td>
<td>recessed lighting</td>
</tr>
<tr>
<td>District heating schedule</td>
<td>Building</td>
<td>On/off</td>
<td>Annual</td>
<td>Hourly</td>
<td>space heating</td>
</tr>
<tr>
<td>Surface temperature (ground)</td>
<td>Building</td>
<td>°C</td>
<td>Annual</td>
<td>Monthly</td>
<td>building in contact with ground</td>
</tr>
<tr>
<td>Heating/ cooling setpoints</td>
<td>Offices, Lecture rooms, Post-graduate rooms, Conference rooms, labs</td>
<td>°C</td>
<td>Annual</td>
<td>Hourly</td>
<td>working hours</td>
</tr>
<tr>
<td>MVHR operation</td>
<td>Offices, Lecture rooms, Post-graduate rooms, Conference rooms, labs</td>
<td>On/off</td>
<td>Annual</td>
<td>Hourly</td>
<td>working hours</td>
</tr>
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</table>
### E.2 Equipment energy rate and heat gain fractions used in simulation

<table>
<thead>
<tr>
<th>Source</th>
<th>Equipment</th>
<th>Energy rate (W)</th>
<th>Heat gain fractions</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Rated Power (W)</td>
<td>Peak/Operational</td>
<td>Standby/</td>
</tr>
<tr>
<td><strong>Computer</strong></td>
<td>Manufacturer A (model A); 2.8 GHz processor, 1 GB RAM</td>
<td>480</td>
<td>73</td>
<td>0</td>
</tr>
<tr>
<td>(ASHRAE, 2009)</td>
<td>Manufacturer A (model B); 2.6 GHz processor, 2 GB RAM</td>
<td>480</td>
<td>49</td>
<td>n/a</td>
</tr>
<tr>
<td></td>
<td>Manufacturer B (model A); 3.0 GHz processor, 2 GB RAM</td>
<td>690</td>
<td>77</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Manufacturer B (model B); 3.0 GHz processor, 2 GB RAM</td>
<td>690</td>
<td>48</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Manufacturer A (model C); 2.3 GHz processor, 3 GB RAM</td>
<td>1200</td>
<td>97</td>
<td>0</td>
</tr>
<tr>
<td>(LBNL, 2007)</td>
<td>Computer</td>
<td>n/a</td>
<td>180.3 (63)</td>
<td>73.97 (63)</td>
</tr>
<tr>
<td>(Menezes et al., 2014)</td>
<td>High-end desktops</td>
<td>n/a</td>
<td>150</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Low-end desktops</td>
<td>n/a</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>(Carolina et al., 2013)</td>
<td>2.3 GHz Intel Core Duo</td>
<td>n/a</td>
<td>69.1</td>
<td>64.1</td>
</tr>
<tr>
<td>Measured</td>
<td>Computer (core i3, 4gb RAM) @ field study</td>
<td></td>
<td>49</td>
<td>2.6</td>
</tr>
<tr>
<td>Value to be used in simulation</td>
<td>Computer (core i3, 4gb RAM)</td>
<td></td>
<td>49</td>
<td>2.6</td>
</tr>
<tr>
<td>Monitor</td>
<td>Manufacturer X (model A); 760 mm screen 383</td>
<td>383</td>
<td>90</td>
<td></td>
</tr>
<tr>
<td>(ASHRAE, 2009)</td>
<td>Manufacturer X (model B); 560 mm screen 360</td>
<td>360</td>
<td>36</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Manufacturer Y (model A), 480</td>
<td>288</td>
<td>28</td>
<td></td>
</tr>
</tbody>
</table>
Appendix E. Building energy model inputs

<table>
<thead>
<tr>
<th>Screen Size</th>
<th>Manufacturer Y (model B), 430 mm screen 240</th>
<th>240</th>
<th>27</th>
</tr>
</thead>
<tbody>
<tr>
<td>Screen Size</td>
<td>Manufacturer Z (model A), 430 mm screen 240</td>
<td>240</td>
<td>29</td>
</tr>
<tr>
<td>Screen Size</td>
<td>Manufacturer Z (model C), 380 mm screen 240</td>
<td>240</td>
<td>19</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>(LBNL, 2007)</th>
<th>Screen LCD</th>
<th>n/a</th>
<th>55.48 (31)</th>
<th>27.61 (32)</th>
<th>1.38 (31)</th>
<th>1.13 (30)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Menezes et al., 2014)</td>
<td>19” LCD screen</td>
<td>n/a</td>
<td>25</td>
<td>128</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Carolina et al., 2013)</td>
<td>19” LCD flat screen</td>
<td>n/a</td>
<td>45</td>
<td>22</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measured</td>
<td>Samsung 19” LED @ field study</td>
<td>n/a</td>
<td>26.7</td>
<td>23.2</td>
<td>0.7</td>
<td>n/a</td>
</tr>
<tr>
<td>Measured</td>
<td>Dell 17” 1400 @ field study</td>
<td>11</td>
<td>0.5</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measured</td>
<td>Computer Screen 19”</td>
<td>29</td>
<td>0.8</td>
<td>0</td>
<td>0</td>
<td>0.4</td>
</tr>
</tbody>
</table>

| Laptop (ASHRAE, 2009) | Manufacturer 1; 2.0 GHz processor, 2 GB RAM, 430 mm screen | 130 | 36 |
| Laptop (ASHRAE, 2009) | Manufacturer 1; 1.8 GHz processor, 1 GB RAM, 430 mm screen | 90 | 23 |
| Laptop (ASHRAE, 2009) | Manufacturer 1; 2.0 GHz processor, 2 GB RAM, 355 mm screen | 90 | 31 | n/a | 0 | 0.25 | 0.75 | 0 |
| Laptop (ASHRAE, 2009) | Manufacturer 2; 2.13 GHz processor, 1 GB RAM, 355 mm screen, | 90 | 29 |

<table>
<thead>
<tr>
<th>LBNL</th>
<th>Notebook</th>
<th>n/a</th>
<th>73.1 (13)</th>
<th>29.48 (13)</th>
<th>15.77 (19)</th>
<th>8.9 (16)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Menezes et al., 2014)</td>
<td>Laptops</td>
<td>n/a</td>
<td>30</td>
<td>99</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Carolina et al., 2013)</td>
<td>2.3 GHz Intel Core Duo</td>
<td>n/a</td>
<td>45.8</td>
<td>30.9</td>
<td>0.3</td>
<td>n/a</td>
</tr>
<tr>
<td>Measured</td>
<td>Laptop (i3, 4gb) 15” @ field study</td>
<td>26.6</td>
<td>10.5</td>
<td>4.2</td>
<td>Accuracy of measuring</td>
<td></td>
</tr>
</tbody>
</table>

which an average 30 W power consumption value may be used. Use 60/40% split between convective and radiative components. In idle mode, monitors have negligible power consumption. Nameplate values should not be used.
Appendix E. Building energy model inputs

<table>
<thead>
<tr>
<th>Device</th>
<th>Value to be used in simulation</th>
<th>Laptop (i3, 4gb) 15(^\circ)</th>
<th>26.6</th>
<th>10.5</th>
<th>4.2</th>
<th>0</th>
<th>0.25</th>
<th>0.75</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Accuracy of measuring device: ±0.2 W</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Only a few laptops are being used in the department therefore measured values for energy rates and ASHRAE data will be used for heat gain fractions.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Laser printer**

| Printing speed up to 10 pages per minute | 430 | 137 |
| Printing speed up to 35 pages per minute | 890 | 74 |
| Printing speed up to 19 pages per minute | 508 | 88 |
| Printing speed up to 17 pages per minute | 508 | 98 |
| Printing speed up to 19 pages per minute | 635 | 110 |
| Printing speed up to 24 page per minute | 1344 | 130 |

**Manufacturer datasheet**

| HP Laserjet 4P C2005a | 704 | 332 | 208 | n/a | 9 (9%) | 92 (99%) |
| HP Laserjet 6P C3980a | 242 | 180 | 128 | 10 | 1.26 | n/a | 16 (22%) | 57 (78%) |
| HP Laserjet 4M C2039a | 770 | 529 | 322 | 6 | n/a | n/a |

| HP Laserjet 4250n (medium size) 40ppm @field study | n/a | 680 | 20 |
| HP Laserjet 5550n (medium size) 27ppm @field study | n/a | 630 | 93 |
| HP Laserjet m402dn (small size) 38ppm@field study | n/a | 591 | 6.1 |

| HP Laserjet 4250n (medium size) 40ppm @field study | 680 | 13 | 1.6 |
| HP Laserjet 5550n (medium size) 27ppm @field study | 630 | 93 | 2.5 |
| HP Laserjet m402dn (small size) 38ppm @field study | 591 | 2.8 | 0.6 |

| HP Laserjet 4250n (medium size) 40ppm | 680 | 13 | 1.6 |
| HP Laserjet 5550n (medium size) 27ppm | 630 | 93 | 2.5 |

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## Appendix E. Building energy model inputs

<table>
<thead>
<tr>
<th>HP Laserjet m402dn (small size) 38ppm</th>
<th>591</th>
<th>2.8</th>
<th>0.6</th>
<th>rates and ASHRAE heat gain data will be used.</th>
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</thead>
<tbody>
<tr>
<td><strong>Copier (large size)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Hosni, Jones, and Xu, 1999)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cannon NP6545</td>
<td>1440</td>
<td>1119</td>
<td>1065</td>
<td>n/a</td>
</tr>
<tr>
<td>Cannon NP6050</td>
<td>1380</td>
<td>1223</td>
<td>1167</td>
<td>n/a</td>
</tr>
<tr>
<td>(Carolina et al., 2013)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Large Network copier</td>
<td>771.6</td>
<td>235.1</td>
<td>29.9</td>
<td>n/a</td>
</tr>
<tr>
<td><strong>Copy machine Large, multiuser, office type</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(ASHRAE, 2009)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1750</td>
<td>800</td>
<td>260</td>
<td>n/a</td>
<td>0</td>
</tr>
<tr>
<td>1440</td>
<td>550</td>
<td>135</td>
<td>n/a</td>
<td>0</td>
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<tr>
<td><strong>Manufacturer datasheet</strong></td>
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<td></td>
<td></td>
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<tr>
<td>Konica Minolta (Copier) @study</td>
<td>1450</td>
<td>1300</td>
<td>812</td>
<td>119</td>
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<tr>
<td><strong>Value to be used in simulation</strong></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Konica Minolta (Copier)</td>
<td>1300</td>
<td>812</td>
<td>119</td>
<td>3</td>
</tr>
<tr>
<td><strong>Microwave</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Carolina et al., 2013)</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Microwave (900 power rating)</td>
<td>n/a</td>
<td>1578.9</td>
<td>210.4</td>
<td>1.9</td>
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<tr>
<td>(LBNL, 2007)</td>
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<td>Microwave oven</td>
<td>1723</td>
<td>1430</td>
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<td>18</td>
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<td>(Ross and Meier, 2001)</td>
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<td>Microwave (standby)</td>
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<td>Microwave F900 @field study</td>
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<tr>
<td>Microwave F900 @field study</td>
<td>1386</td>
<td>2.88</td>
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<tr>
<td><strong>Value to be used in simulation</strong></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Microwave F900</td>
<td>1386</td>
<td>2.88</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td><strong>Coffee maker</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Hosni, Jones, and Xu, 1999)</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Coffee machine</td>
<td>750</td>
<td>350</td>
<td>25</td>
<td>25</td>
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<tr>
<td>(LBNL, 2007)</td>
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<td></td>
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<tr>
<td>Coffee maker (off)</td>
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<td>1.14</td>
<td>12</td>
<td></td>
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<tr>
<td>(ASHRAE, 2009)</td>
<td></td>
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<td></td>
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<tr>
<td>Coffee maker</td>
<td>1500</td>
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<td>450 (0.3)</td>
<td>450 (0.3)</td>
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<td><strong>Value to be used in simulation</strong></td>
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<td></td>
<td></td>
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<tr>
<td>Coffee maker</td>
<td>350</td>
<td>25</td>
<td>25</td>
<td>0.3</td>
</tr>
</tbody>
</table>
## Appendix E. Building energy model inputs

<table>
<thead>
<tr>
<th>Refrigerator</th>
<th>Carollina et al., (2013)</th>
<th>Small Fridge (150L)</th>
<th>98.8</th>
<th>26.4</th>
<th>0</th>
<th>n/a</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Menezes et al., (2014)</td>
<td>Fridge (Large)</td>
<td>n/a</td>
<td>120</td>
<td>100</td>
<td>0</td>
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<tr>
<td>Manufacturer</td>
<td>Refrigerator (85L) LG</td>
<td>Manufacturer label</td>
<td>150</td>
<td>42</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Value to be used in simulation</td>
<td>Refrigerator (85L) LG</td>
<td></td>
<td>42</td>
<td>0</td>
<td>0</td>
<td>0.25</td>
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<tr>
<td></td>
<td></td>
<td>Manufacturer data for energy rates and assumed heat gain data will be used as there is no reliable source available for heat gain fractions.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Toaster      | ASHRAE, (2009)           | Toaster (4 slice)   | 1788 | 879  | 293 (0.33) | 59 (0.07) | 410 (0.47) | 117 (0.13) |
|--------------|--------------------------| Toaster (2 slice) @field study | 860  | 650  | 0        |      |      |    |
| Value to be used in simulation | Toaster (2 slice) |                      | 650  | 0    | 0.33     | 0.07  | 0.47   | 0.13 |
|              |                          | Manufacturer data for energy rates and ASHRAE heat gain data will be used. |

| Electric Kettle | Consumer Affairs, (2011) | Brand 1 | 1200 | 1188 |
|                |                          | Brand 2 | 1350 | 1531 |
|                |                          | Brand 3 | 1200 | 1128 |
|                |                          | Brand 4 | 850  | 819  |
|                |                          | Brand 5 | 1850 | 2025 |
|                |                          | Brand 6 | 2200 | 1735 |
|                |                          | Brand 7 | 1500 | 1555 |
|                |                          | Brand 8 | 2000 | 2280 |
|                |                          | Brand 9 | 1200 | 1145 |
| Manufacturer label | Electric Kettle (1.5L) @field study | 1500 | 1550 |
| Measured | Electric Kettle (1.5L) @field study | 1550 | 1526 |
|                | Electric Kettle (1.5L) | 1526 | 0.2  | 0.3  | 0.5 | 0 |
|              |                          | Measured data for energy rates and assumed heat gain data will be used as no reliable sources were found for heat gain fractions |

| Projector | Manufacturer datasheet | Digital projector (EPSON) 475Wi @field study | 475  | 275  | 8.3 | 0.3 |
|           |                          | Digital projector (EPSON) 475Wi | 275  | 8.3  | 0.3 | 0   | 0.1 | 0.9 | 0 |
|           |                          | Most of the digital projectors are from EPSON therefore this model data for energy rates will be |
Appendix E. Building energy model inputs

<table>
<thead>
<tr>
<th>Manufacturer datasheet</th>
<th>LED TV (55&quot;)</th>
<th>80</th>
<th>57</th>
<th>0.5</th>
<th>0</th>
<th>0.1</th>
<th>0.9</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>LG @field study</td>
<td>LED TV (55&quot;)</td>
<td>57</td>
<td>0.5</td>
<td>0</td>
<td>0.1</td>
<td>0.9</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

Manufacturer data for energy rates and assumed heat gain data will be used as there are no reliable sources for heat gain fractions.

References


Appendix F. Calibration scripts

F.1 RVI File for running batch simulations in JEPlus

In Chapter 5, the *.rvi file was used in JEPlus for extracting the simulation results from each iteration done by EnergyPlus.

```json
{
  "notes" : "Some notes about this RVX",

  "rvis" : [ 
    
    {
      "fileName" : "MonthlyMeters.rvi",
      "tableName" : "MonthlyMeters",
      "frequency" : "Monthly",
      "usedInCalc" : true
    }
  ],

  "sqls" : [ 
  ],

  "scripts" : [ 
    
    {
      "fileName" : "CalcASHRAE14.py",
      "pythonVersion" : "python3",
      "onEachJob" : true,
      "arguments" : "MonthlyMeters;ref.csv",
      "tableName" : "CVRMSE"
    }
  ],

  "userVars" : [ 
    
    {
      "identifier" : "v0",
      "formula" : "c3+c5",
      "caption" : "CVRMSE Electricity[\%]",
      "report" : true
    },

    {
      "identifier" : "v1",
      "formula" : "c4+c6",
      "caption" : "NMBE Electricity[\%]",
      "report" : true
    },

    {
      "identifier" : "v2",
      "formula" : "c7",
      "caption" : "CVRMSE Heating[\%]",
      "report" : true
    }
  ]
}
```
Appendix F. Calibration scripts

```
"report" : true,
},
{
"identifier" : "v3",
"formula" : "c8",
"caption" : "NMBE Heating[\%]",
"report" : true
}
],
"constraints" : [
],
"objectives" : [
{
"identifier" : "t1",
"formula" : "v0+v2",
"caption" : "Sum CVRMSE[\%",
"scaling" : false,
"min" : "0",
"max" : "100000",
"weight" : "1.0"
},
{
"identifier" : "t2",
"formula" : "abs(v1)+abs(v3)",
"caption" : "Sum |NMBE|[\%]",
"scaling" : false,
"min" : "0",
"max" : "1000",
"weight" : "1.0"
}
]
```
F.2 ASHRAE script for calculation of Cv(RMSE) and NMBE

In Chapter 5, the following python script was used to calculate the CvRMSE and NMBE as per ASHRAE Guide 14 using jEPlus.

```python
import pandas as pd
import numpy as np
import csv
import sys
import re

# function which calculates the cv(rmse)
def cvrmse_function(observed, predicted, N):
    error = observed - predicted
    sqerror = error ** 2
    sumsqerror = np.sum(sqerror)
    meansqerror = sumsqerror / N
    rmse = np.sqrt(meansqerror)
    cvrmse = 100 * rmse / np.mean(observed);
    return cvrmse

# function which calculates the normalized mean bias error (nmbe)
def nmbe_function(observed, predicted, N):
    error = predicted - observed
    sbe = np.sum(error)
    mbe = sbe / N
    nmbe = 100 * mbe / np.mean(observed)
    return nmbe

# This file should be run within each job folder
# Arguments:
#   sys.argv[1] - project's base folder where the project files, including
#                 the reference data file, are located
#   sys.argv[2] - output folder of the project where job folders are
#                 located
#   sys.argv[3] - user-defined output table name + .csv
#   sys.argv[4] - Other arguments specified in the RVX file, in this case,
#                 the input table file name without extension, followed by
#                 the reference data file name. ("MonthlyMeters;ref.csv")

args = sys.argv[4].split(';

refdata = pd.read_csv(sys.argv[1] + args[1]) #read data from the reference
       # file (path passed from the script)
in_file = sys.argv[2] + args[0] + ".csv"
indata = pd.read_csv(in_file)
rowcolno = indata.shape
```
Appendix F. Calibration scripts

```python
# take heading row from the reference file
heading = list(refdata.ix[:0])
newheading = heading[0:1]
for h in heading[1:]:
    newheading += ['CVRMSE:' + re.sub(r'\s*\[.*\].*', '[%]', h)]
    newheading += ['NMBE:' + re.sub(r'\s*\[.*\].*', '[%]', h)]

outname = sys.argv[3]  # output file name from the parameter passed to the script
rmsedata = ['NA']

with open(outname, "w", newline='') as outfile:
    output = csv.writer(outfile)
    output.writerow(newheading)
    # for column in range(1, rowcolno[1]):
    for column in heading[1:]:
        observed = np.array(refdata.loc[:, column])
        predicted = np.array(indata.loc[:, column])
        rmsedata.append(cvrmse_function(observed, predicted, rowcolno[0]))
        rmsedata.append(nmbe_function(observed, predicted, rowcolno[0]))
    output.writerow(rmsedata)
```
Appendix G. EnergyPlus text file sample (shortened preview)

Chapter 5 and Chapter 6 of the thesis used the EnergyPlus files for calibration and multi-objective optimisation and an example text file (shortened) of the same is given below. In Chapter 5, during calibration the EnergyPlus file was modified for tuning 25 parameters and references were inserted (e.g. @@text@@) that were auto-tuned through NSGA-II using jEPlus. Similarly, in Chapter 6, during multi-objective optimisation of retrofit measures the references were inserted based on the adopted measures (e.g. insulation conductivity, glazing u-value etc.) in the EnergyPlus file of respective models that were optimised by jEPlus during the search for optimal solutions.

```plaintext
!-Generator IDFEditor 1.50
!-Option SortedOrder
!
!- NOTE: All comments with '!'- are ignored by the IDFEditor and are generated automatically.
!- Use '!' comments if they need to be retained when using the IDFEditor.

!- ---------- ALL OBJECTS IN CLASS: VERSION ----------
Version,
8.8;  !- Version Identifier

!- ---------- ALL OBJECTS IN CLASS: SIMULATIONCONTROL ----------
SimulationControl,
Yes,  !- Do Zone Sizing Calculation
Calculation
Yes,  !- Do System Sizing Calculation
Calculation
No,  !- Do Plant Sizing Calculation
Sizing Periods
Yes;  !- Run Simulation for Weather File Run Periods
Weather File Run Periods
6;  !- Number of Timesteps per Hour

!- ---------- ALL OBJECTS IN CLASS: CONVERGENCELIMITS ----------
ConvergenceLimits,
1;  !- Minimum System Timestep [minutes]

!- ---------- ALL OBJECTS IN CLASS: SITE:LOCATION ----------
Site:Location,
Galway,  !- Name
53.27,  !- Latitude (deg)
9.06,  !- Longitude (deg)
0,  !- Time Zone (hr)
25;  !- Elevation (m)

!- ---------- ALL OBJECTS IN CLASS: SCHEDULETYPELIMITS ----------
ScheduleTypeLimits,
Schedule Type Limits 2,  !- Name
0,  !- Lower Limit Value
4,  !- Upper Limit Value
Continuous;  !- Numeric Type

ScheduleTypeLimits,
101 Thermostat Schedule Type Limits,  !- Name
0,  !- Lower Limit Value
4,  !- Upper Limit Value
DISCRETE;  !- Numeric Type

!- ---------- ALL OBJECTS IN CLASS: SCHEDULE:DAY:INTERVAL ----------
Schedule:Day:Interval,
Cl_Office_101_Lighting_sch Day Schedule - Sun,  !- Name
Schedule Type Limits 2,  !- Schedule Type Limits Name
No,  !- Interpolate to Timestep
24:00,  !- Time 1 [hh:mm]
0;  !- Value Until Time 1
```

---

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### Appendix G. EnergyPlus textfile sample

```plaintext
Cl_Office_101_Lighting.sch  Day Schedule -
Mon.  !- Name Schedule Type Limits Name

<table>
<thead>
<tr>
<th>Schedule Type Limits Name</th>
<th>!- Schedule Type Limits Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>!- Interpolate to Time 1</td>
<td>!- Interpolate to Time 1</td>
</tr>
<tr>
<td>Time 1 (hh:mm)</td>
<td>Time 1 (hh:mm)</td>
</tr>
<tr>
<td>!- Value Until Time 1</td>
<td>!- Value Until Time 1</td>
</tr>
<tr>
<td>24:00</td>
<td>21:00</td>
</tr>
</tbody>
</table>

Schedule:Day:Interval,
Medium Office HtgSetp Rule 1 Day Schedule 1, !- Name
Temperature 37, !- Schedule Type
Limits Name

<table>
<thead>
<tr>
<th>Schedule Type Limits Name</th>
<th>!- Interpolate to Time 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>!- Value Until Time 1</td>
<td>!- Value Until Time 1</td>
</tr>
<tr>
<td>24:00</td>
<td>21:00</td>
</tr>
</tbody>
</table>

Schedule:Day:Interval,
Medium Office ClgSetp Rule 1 Day Schedule 1, !- Name
Temperature 37, !- Schedule Type
Limits Name

<table>
<thead>
<tr>
<th>Schedule Type Limits Name</th>
<th>!- Interpolate to Time 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>!- Value Until Time 1</td>
<td>!- Value Until Time 1</td>
</tr>
<tr>
<td>24:00</td>
<td>21:00</td>
</tr>
</tbody>
</table>

Schedule:Day:Interval,
Medium Office ClgSetp Rule 2 Day Schedule 1, !- Name
Temperature 37, !- Schedule Type
Limits Name

<table>
<thead>
<tr>
<th>Schedule Type Limits Name</th>
<th>!- Interpolate to Time 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>!- Value Until Time 1</td>
<td>!- Value Until Time 1</td>
</tr>
<tr>
<td>24:00</td>
<td>21:00</td>
</tr>
</tbody>
</table>

Schedule:Day:Interval,
Medium Office ClgSetp Summer Design Day 1, !- Name
Temperature 37, !- Schedule Type
Limits Name

<table>
<thead>
<tr>
<th>Schedule Type Limits Name</th>
<th>!- Interpolate to Time 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>!- Value Until Time 1</td>
<td>!- Value Until Time 1</td>
</tr>
<tr>
<td>24:00</td>
<td>21:00</td>
</tr>
</tbody>
</table>

Schedule:Day:Interval,
Medium Office ClgSetp Summer Design Day 2, !- Name
Temperature 36, !- Schedule Type
Limits Name

<table>
<thead>
<tr>
<th>Schedule Type Limits Name</th>
<th>!- Interpolate to Time 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>!- Value Until Time 1</td>
<td>!- Value Until Time 1</td>
</tr>
<tr>
<td>24:00</td>
<td>21:00</td>
</tr>
</tbody>
</table>

Schedule:Day:Interval,
Medium Office ClgSetp Winter Design Day 1, !- Name
Temperature 37, !- Schedule Type
Limits Name

<table>
<thead>
<tr>
<th>Schedule Type Limits Name</th>
<th>!- Interpolate to Time 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>!- Value Until Time 1</td>
<td>!- Value Until Time 1</td>
</tr>
<tr>
<td>24:00</td>
<td>21:00</td>
</tr>
</tbody>
</table>

Schedule:Day:Interval,
Medium Office ClgSetp Winter Design Day 2, !- Name
Temperature 36, !- Schedule Type
Limits Name

<table>
<thead>
<tr>
<th>Schedule Type Limits Name</th>
<th>!- Interpolate to Time 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>!- Value Until Time 1</td>
<td>!- Value Until Time 1</td>
</tr>
<tr>
<td>24:00</td>
<td>21:00</td>
</tr>
</tbody>
</table>
```

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Appendix G. EnergyPlus textfile sample

24:00,
1;                        !- Time 3 (hh:mm)
Schedule:Day:Interval,
Schedule Day 28, OnOff,
Limits Name No,
Timestep 07:00,
1, 19:00,
1, 22:00,
1,
24:00,
1;                        !- Value Until Time 3
Schedule:Day:Interval,
Schedule Day 25, OnOff,
Limits Name No,
Timestep 24:00,
1;                        !- Value Until Time 1
Schedule:Day:Interval,
Schedule Day 19, OnOff,
Limits Name No,
Timestep 07:00,
1, 19:00,
1, 22:00,
1,
24:00,
1;                        !- Value Until Time 3
Schedule:Day:Interval,
Schedule Day 30, OnOff,
Limits Name No,
Timestep 24:00,
0;                        !- Value Until Time 1
Schedule:Day:Interval,
Schedule Day 17, OnOff,
Limits Name No,
Timestep 24:00,
0;                        !- Value Until Time 1
Schedule:Day:Interval,
Cl_Office_101a_Lighting_sch Day Schedule - Sun,
Limits Name No,
Timestep 24:00,
0;                        !- Value Until Time 1
Schedule:Day:Interval,
Cl_Office_101a_Lighting_sch Day Schedule - Mon,
Limits Name No,
Timestep 08:00,
0;                        !- Value Until Time 1
09:00,
0.5,
10:00,
0.8,
12:00,
0.9,
13:00,
0.8,
15:00,
0.9,
16:00,
0.9,
17:00,
0.8,
24:00,
0;                        !- Value Until Time 2
0;                        !- Value Until Time 2
10;                       !- Value Until Time 3
11;                       !- Value Until Time 3
12;                       !- Value Until Time 3
Appendix G. EnergyPlus textfile sample

0;                   !- Value Until Time 1

Schedule:Day:Interval,  
Cl_Office_101_Equipment_sch Day Schedule - Mon,  !- Name  
Schedule Type Limits 2,  !- Schedule Type  
Limits Name  
No,  
Timestep  
08:00,  
0,  
09:00,  
0.07,  
0.08,  
10:00,  
11:00,  
12:00,  
13:00,  
14:00,  
15:00,  
16:00,  
17:00,  
18:00,  
19:00,  
20:00,  
21:00,  
22:00,  
23:00,  
0;  

-------

Schedule:Day:Interval,  
Hot Water Temperature Default 21,  !- Name  
Temperature,  !- Schedule Type  
Limits Name  
No,  
Timestep  
02:00,  
04:00,  
06:00,  
08:00,  
0.09,  
10:00,  
12:00,  
14:00,  
16:00,  
18:00,  
0;  

-------

Schedule:Day:Interval,  
Lab_217_Equipment_sch Day Schedule - Mon,  !- Name  
Schedule Type Limits 2,  !- Schedule Type  
Limits Name  
No,  
Timestep  
08:00,  
0,  
09:00,  
0.07,  
0.08,  
10:00,  
11:00,  
12:00,  
13:00,  
14:00,  
15:00,  
16:00,  
17:00,  
0;  

--------
Appendix G. EnergyPlus textfile sample

1-!- ----------- ALL OBJECTS IN CLASS: CONSTRUCTION -----------

Construction,
CRECS BEFORE-1980 EXTROOF IEAD CLIMATEZONE
4A, !- Name
Roof Membrane, !- Outside Layer
IEAD NonRes Roof Insulation-2.04, !- Layer 2
Metal Decking; !- Layer 3

Construction,
Geo_ceilin, !- Name
F16 ACOUSTIC TILE; !- Outside Layer

Construction,
Geo_DoublePane, !- Name
Double_glz; !- Outside Layer

FENESTRATION:DETAILED ===========

BuildingSurface:Detailed,
101_Srf_0, !- Name
Wall,
Geo_exterior_wall, !- Construction Name
101, !- Zone Name
Outdoors,

Condition,
!- Outside Boundary
Condition Object
SunExposed,
WindExposed,
Ground

-!- ----------- ALL OBJECTS IN CLASS: BUILDINGSURFACE:DETAILED -----------

BuildingSurface:Detailed,
101_Srf_0, !- Name
Wall,
Geo_exterior_wall, !- Construction Name
101, !- Zone Name
Outdoors,

Condition,
!- Outside Boundary
Condition Object
SunExposed,
WindExposed,
Ground

-!- ----------- ALL OBJECTS IN CLASS: FENESTRATION:DETAILED -----------

FenestrationSurface:Detailed,
101_Srf_0_glz_0, !- Name
Window,
Geo_DoublePane, !- Construction Name
101_Srf_0,

Name,
!- Outside Boundary
Condition Object
!- View Factor to

Ground

-!- ----------- ALL OBJECTS IN CLASS: WINDOWPROPERTY:SHADINGCONTROL -----------

WindowProperty:ShadingControl,
ShadingControl1,
!- Name
InteriorBlinds,

ShadingName
OnIfHighSolarOnWindow,

Type
!- Shading Control

-!- ----------- ALL OBJECTS IN CLASS: PEOPLE -----------

People,
101_PeopleObject,
!- Name
101,
!- Zone or ZoneList

Name
Cl_Office_101_Occupancy_sch Year Schedule,

-!- ----------- ALL OBJECTS IN CLASS: CALCULATION METHOD -----------

CalculationMethod
0.079,

0.3,

-!- ----------- ALL OBJECTS IN CLASS: LIGHTS -----------

Lights,
101_LightsObject,
!- Name
101,
!- Zone or ZoneList

Name
Cl_Office_101_Lighting_sch Year Schedule,

CalculationMethod
0.079,

0.3,
Appendix G. EnergyPlus textfile sample

,                      !- Watts per Person
,(W/person)          
,                                   !- Return Air Fraction
0.1,                     !- Fraction Radiant
,                                   !- Fraction Visible
,                                   !- Fraction Replaceable

--------------------------

!- All objects in class: 
ZONEINfiltration:DESIGNFLOWRATE ===========

ZoneInfiltration:DesignFlowRate, ! Name
  Space Infiltration Design Flow Rate 13, !- Schedule Name
  AirChanges/Hour, Calculation Method
  (m3/s)
  0.0003,
  Area (m3/s-m2)
  !- Flow per Zone Floor
  Surface Area (m3/s-m2)
  $\#\#\#\#\#$
  per Hour (1/hr)
  !- Constant Term
  Coefficient ,
  Coefficient
  !- Temperature Term
  Coefficient 
  !- Velocity Term
  Term Coefficient

--------------------------

!- All objects in class: 
ZONEVENTILATION:DESIGNFLOWRATE ===========

ZoneVentilation:DesignFlowRate, ! Name
  Natural Ventilation, !- Schedule Name
  Always On Discrete hvac_library, !- Schedule Name
  AirChanges/Hour, Calculation Method
  (m3/s)
  0,
  Floor Area (m3/s-m2)
  0,
  Person (m3/s-person)
  5,
  Air Changes per Hour
  (1/hr)
  Natural, 0, (Pa)
  1
  !- Fan Total Efficiency
  !- Fan Pressure Rise
  0.606,
  Coefficient 0.03636,
  Coefficient 0.177,
  Coefficient
  !- Temperature Term
  !- Velocity Term
  Term Coefficient 22.5,
  Temperature [C]
  !- Minimum Indoor
  Temperature Schedule Name 100,
  Temperature [C]
  !- Maximum Indoor
  Temperature Schedule Name 10 (deltaC)
  ,
  Schedule Name -100,
  Temperature [C]
  Temperature Schedule Name 100,
  Temperature [C]

-------------------------------------

DesignSpecification:ZoneAirDistribution, ! Name
101 Design Spec Zone Air Dist, !- Schedule Name
1, !- Zone Air Distribution
Effectiveness in Cooling Mode (dimensionless)
1;
Effectiveness in Heating Mode (dimensionless)

--------------------------

!- All objects in class: 
SIZING:PARAMETERS ===========

Sizing:Parameters,
  1.25, !- Heating Sizing Factor
  1.15; !- Cooling Sizing Factor

--------------------------

!- All objects in class: 
SIZING:ZONE ===========

Sizing:Zone,
  101,
  !- Zone or ZoneList
  SupplyAirTemperature, !- Cooling Design Air
  Supply Air Temperature Input Method
  14, !- Zone Cooling Design
  Supply Air Temperature (C)
  11.11, !- Zone Cooling Design
  Supply Air Temperature Difference (deltaC)
  !- Zone Heating Design
  Supply Air Temperature Input Method
  40, !- Zone Heating Design
  Supply Air Temperature (C)
  11.11, !- Zone Heating Design
  Supply Air Temperature Difference (deltaC)
  0.0085,
  Supply Air Humidity Ratio (kgWater/kgDryAir)
  0.008,
  Supply Air Humidity Ratio (kgWater/kgDryAir)
  0,
  Design Specification
  102 DDA,
  Outdoor Air Object Name
  !- Zone Heating Sizing
  Factor
  ,
  !- Zone Cooling Sizing
  Factor
  DesignDay,
  Flow Method
  0,
  Flow Rate (m3/s)
  0.000762,
  !- Cooling Minimum
  Air Flow per Zone Floor Area (m3/s-m2)
  0,
  !- Cooling Minimum
  Air Flow (m3/s)
  0,
  !- Heating Minimum
  Air Flow Fraction
  DesignDay,
  Flow Method
  0,
  !- Heating Design Air
  Flow Rate (m3/s)
  0.002032,
  !- Heating Maximum
  Air Flow per Zone Floor Area (m3/s-m2)
  0.1415762,
  !- Heating Maximum
  Air Flow (m3/s)
  0.3,
  !- Heating Maximum
  Air Flow Fraction
  101 Design Spec Zone Air Dist, !- Design Specification Zone Air Distribution Object Name
  No;
  !- Account for Dedicated Outside Air System

------------------------------

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Appendix G. EnergyPlus textfile sample

```plaintext
Sizing:Plant,
  Plant Loop 1, !- Plant or Condenser
Loop Name   Heating, !- Loop Type
  $2, !- Design Loop Exit
Temperature [C] 11, !- Loop Design
Temperature Difference (deltaT)
  NonCoincident, !- Sizing Option
  1, !- Zone Timsteps in
Averaging Window
  None; !- Coincident Sizing
Factor Mode

!- =========== ALL OBJECTS IN CLASS: ZONECONTROL: THERMOSTAT ===========
ZoneControl:Thermostat,
  101 Thermostat, !- Name
  101, !- Zone or ZoneList
Name
  101 Thermostat Schedule, !- Control Type
Schedule Name
  ThermostatSetpoint:DualSetpoint; !- Control 1
Object Type
dualsetPINThermostat101; !- Control 1 Name

!- =========== ALL OBJECTS IN CLASS: ZONEHVAC:BASEBOARD: CONVECTIVE: WATER ===========
ZONEHVAC: Baseboard: Convective: Water,
  HW Baseboard, !- Name
District heating schedule, !- Availability
Schedule Name
  Node 31, !- Inlet Node Name
Node 32, !- Outlet Node Name
  HeatingDesignCapacity, !- Heating Design
Capacity Method
  Autosize,
Capacity (W) 0,
  !- Heating Design
Capacity Per Floor Area (W/m2)
  5.5, !- Fraction of
Autosized Heating Design Capacity
  Autosize,
  !- U-Factor Times Area
Value (W/K)
  0.801;
  !- Maximum Water Flow
Tolerance

!- =========== ALL OBJECTS IN CLASS: BRANCH ===========
Branch,
  Plant Loop 1 Supply Inlet Branch, !- Name
  !- Pressure Drop Curve
Name
  Pump:VariableSpeed, !- Component 1 Object
Type
  VarSpdPump, !- Component 1 Name
Node Name
  Node 87, !- Component 1 Inlet
Node 84; !- Component 1 Outlet
Node Name
Branch,
  Plant Loop 1 Supply Branch 1, !- Name
  !- Pressure Drop Curve
Name
  District Heating, !- Component 1 Object
Type
  District Heating, !- Component 1 Name
Node Name
  Node 89, !- Component 1 Inlet
Node 93; !- Component 1 Outlet
Node Name

!- =========== ALL OBJECTS IN CLASS: BRANCHLIST ===========
BranchList,
  Plant Loop 1 Supply Branches, !- Name
  Plant Loop 1 Supply Inlet Branch, !- Branch 1
Name
  Plant Loop 1 Supply Branch 1, !- Branch 2 Name
  Plant Loop 1 Supply Outlet Branch; !- Branch 3 Name

BranchList,
  Plant Loop 1 Demand Branches, !- Name
  Plant Loop 1 Demand Inlet Branch, !- Branch 1
Name
  Plant Loop 1 Demand Branch 1, !- Branch 2 Name
  Plant Loop 1 Demand Branch 2, !- Branch 3 Name
  Plant Loop 1 Demand Branch 3, !- Branch 4 Name
  Plant Loop 1 Demand Branch 4, !- Branch 5 Name
  Plant Loop 1 Demand Branch 5, !- Branch 6 Name
  Plant Loop 1 Demand Branch 6, !- Branch 7 Name
  Plant Loop 1 Demand Branch 7, !- Branch 8 Name
  Plant Loop 1 Demand Branch 8, !- Branch 9 Name
  Plant Loop 1 Demand Branch 9, !- Branch 10 Name

Name
  Plant Loop 1 Demand Branch 10, !- Branch 11 Name
  Plant Loop 1 Demand Branch 11, !- Branch 12 Name
  Plant Loop 1 Demand Branch 12, !- Branch 13 Name
  Plant Loop 1 Demand Branch 13, !- Branch 14 Name
  Plant Loop 1 Demand Branch 14, !- Branch 15 Name
  Plant Loop 1 Demand Branch 15, !- Branch 16 Name
  Plant Loop 1 Demand Branch 16, !- Branch 17 Name
  Plant Loop 1 Demand Branch 17, !- Branch 18 Name
  Plant Loop 1 Demand Branch 18, !- Branch 19 Name
  Plant Loop 1 Demand Branch 19, !- Branch 20 Name
  Plant Loop 1 Demand Branch 20, !- Branch 21 Name
  Plant Loop 1 Demand Branch 21, !- Branch 22 Name
  Plant Loop 1 Demand Branch 22, !- Branch 23 Name
  Plant Loop 1 Demand Branch 23, !- Branch 24 Name
  Plant Loop 1 Demand Branch 24, !- Branch 25 Name
  Plant Loop 1 Demand Branch 25, !- Branch 26 Name
  Plant Loop 1 Demand Branch 26, !- Branch 27 Name
  Plant Loop 1 Demand Bypass Branch, !- Branch 28 Name
  Plant Loop 1 Demand Outlet Branch; !- Branch 29 Name

!- =========== ALL OBJECTS IN CLASS: CONNECTOR: SPLITTER ===========
Connector:Splitter,
  Plant Loop 1 Supply Splitter, !- Name
  Plant Loop 1 Supply Inlet Branch, !- Inlet Branch Name
  Plant Loop 1 Supply Branch 1; !- Outlet Branch 1 Name

Connector:Splitter,
  Plant Loop 1 Demand Splitter, !- Name
  Plant Loop 1 Demand Inlet Branch, !- Inlet Branch Name
  Plant Loop 1 Demand Branch 1, !- Outlet Branch 1 Name
  Plant Loop 1 Demand Branch 2, !- Outlet Branch 2 Name
  Plant Loop 1 Demand Branch 3, !- Outlet Branch 3 Name
  Plant Loop 1 Demand Branch 4, !- Outlet Branch 4 Name
  Plant Loop 1 Demand Branch 5, !- Outlet Branch 5 Name
  Plant Loop 1 Demand Branch 6, !- Outlet Branch 6 Name

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Plant Loop 1 Demand Branch 7, !- Outlet Branch
7 Name
Plant Loop 1 Demand Branch 8, !- Outlet Branch
8 Name
Plant Loop 1 Demand Branch 9, !- Outlet Branch
9 Name
Plant Loop 1 Demand Branch 10, !- Outlet Branch
10 Name

------------ ALL OBJECTS IN CLASS:
CONNECTORLIST

ConnectorList,
Plant Loop 1 Supply Connector List, !- Name
Connector:Splitter, !- Connector 1 Object
Type
Plant Loop 1 Supply Splitter, !- Connector 1 Name
Connector:Mixer, !- Connector 2 Object
Type
Plant Loop 1 Supply Mixer; !- Connector 2 Name
ConnectorList,
Plant Loop 1 Demand Connector List, !- Name
Connector:Splitter, !- Connector 1 Object
Type
Plant Loop 1 Demand Splitter, !- Connector 1 Name
Connector:Mixer, !- Connector 2 Object
Type
Plant Loop 1 Demand Mixer; !- Connector 2 Name

------------ ALL OBJECTS IN CLASS:
OUTDOORAIR:NODE

OutdoorAir:Node,
Model Outdoor Air Node; !- Name

------------ ALL OBJECTS IN CLASS:
PIPE:ADIABATIC

Pipe:Adiabatic,
Plant Loop 1 Supply Outlet Pipe, !- Name
Plant Loop 1 Supply Outlet Pipe Node; !- Inlet
Node Name
Node 88; !- Outlet Node Name
Pipe:Adiabatic,
Plant Loop 1 Demand Inlet Pipe, !- Name
Node 90, !- Inlet Node Name
Plant Loop 1 Demand Inlet Pipe Node; !- Outlet
Node Name

------------ ALL OBJECTS IN CLASS:
PUMP:VARIABLESPEED

Pump:VariableSpeed,
Var Spd Pump, !- Name
Node 87, !- Inlet Node Name
Node 84, !- Outlet Node Name
Autosize, !- Design Maximum Flow
Rate (m3/s)
179352, !- Design Pump Head
(Pa)
Autosize, !- Design Power
Consumption (W)
0.9, !- Motor Efficiency
0.9, !- Fraction of Motor
Inefficiencies to Fluid Stream
0, !- Coefficient 1 of
the Part Load Performance Curve
0, !- Coefficient 2 of
the Part Load Performance Curve
0, !- Coefficient 3 of
the Part Load Performance Curve
0, !- Coefficient 4 of
the Part Load Performance Curve
0, !- Design Minimum Flow
Rate (m3/s)
Continuous, !- Pump Control Type
!- Pump Flow Rate
Schedule Name
, !- Pump Curve Name

------------ ALL OBJECTS IN CLASS:
DISTRICTHEATING

DistrictHeating,
District Heating, !- Name
Node 89, !- Hot Water Inlet
Node Name
Node 93, !- Hot Water Outlet
Node Name
Node 1000000; !- Nominal Capacity

------------ ALL OBJECTS IN CLASS: PLANTLOOP

PlantLoop,
Plant Loop 1, !- Name
Water, !- Fluid Type
Water, !- User Defined Fluid
Type
Plant Loop 1 Operation Schemes, !- Plant
Equipment Operation Scheme Name
Node 88, !- Loop Temperature
Setpoint Node Name
100, !- Maximum Loop
Temperature (°C)
0, !- Minimum Loop
Temperature (°C)
AutoSz,
Rate (m3/s)
0, !- Minimum Loop Flow
Rate (m3/s)
Autocalc,
!- Plant Loop Volume
Node 87, !- Plant Side Inlet
Node Name
Node 88, !- Plant Side Outlet
Node Name
Plant Loop 1 Supply Branches, !- Plant Side
Branch List Name
Plant Loop 1 Supply Connector List, !- Plant
Side Connector List Name
Node 89, !- Demand Side Inlet
Node Name
Node 91, !- Demand Side Outlet
Node Name
Plant Loop 1 Demand Branches, !- Demand Side
Branch List Name
Plant Loop 1 Demand Connector List, !- Demand
Side Connector List Name
Optimal,
!- Load Distribution
Scheme
, !- Availability Manager
List Name
SingleSetpoint;
Calculation Scheme

------------ ALL OBJECTS IN CLASS:
PLANTEQUIPMENTLIST

------------ ALL OBJECTS IN CLASS:
VFDCONTROL

VFDControl,
Plant Loop 1, !- Name
Motor, !- VFD Control Type
Motor, !- Pump rpm Schedule
Motor, !- Minimum Pressure
Schedule [Pa]
, !- Maximum Pressure
Schedule [Pa]
, !- Minimum RPM Schedule
, !- Maximum RPM Schedule
, !- Zone Name
Fraction
PowerPerFlowPerPressure, !- Design Power
Sizing Method
348701.1, !- Design Electric
Power per Unit Flow Rate (W/(m3/s))
1.282051282, !- Design Shaft Power
per Unit Flow Rate per Unit Head (W/(m3/s) - Pa)
0, !- Design Minimum Flow
Rate Fraction

------------ ALL OBJECTS IN CLASS:
AVAILABILITYMANAGER

AvailabilityManager,
Plant Loop 1, !- Name
Node 89, !- Demand Side Inlet
Node Name
Node 91, !- Demand Side Outlet
Node Name
Plant Loop 1 Demand Branches, !- Demand Side
Branch List Name
Plant Loop 1 Demand Connector List, !- Demand
Side Connector List Name
Optimal,
!- Load Distribution
Scheme
, !- Availability Manager
List Name
SingleSetpoint;
Calculation Scheme

------------ ALL OBJECTS IN CLASS:
PLANTEQUIPMENTLIST

------------ ALL OBJECTS IN CLASS:
PLANTLOOP

PlantLoop,
Plant Loop 1, !- Name
Water, !- Fluid Type
Water, !- User Defined Fluid
Type
Plant Loop 1 Operation Schemes, !- Plant
Equipment Operation Scheme Name
Node 88, !- Loop Temperature
Setpoint Node Name
100, !- Maximum Loop
Temperature (°C)
0, !- Minimum Loop
Temperature (°C)
AutoSz,
Rate (m3/s)
0, !- Minimum Loop Flow
Rate (m3/s)
Autocalc,
!- Plant Loop Volume
Node 87, !- Plant Side Inlet
Node Name
Node 88, !- Plant Side Outlet
Node Name
Plant Loop 1 Supply Branches, !- Plant Side
Branch List Name
Plant Loop 1 Supply Connector List, !- Plant
Side Connector List Name
Node 89, !- Demand Side Inlet
Node Name
Node 91, !- Demand Side Outlet
Node Name
Plant Loop 1 Demand Branches, !- Demand Side
Branch List Name
Plant Loop 1 Demand Connector List, !- Demand
Side Connector List Name
Optimal,
!- Load Distribution
Scheme
, !- Availability Manager
List Name
SingleSetpoint;
Calculation Scheme

------------ ALL OBJECTS IN CLASS:
PLANTEQUIPMENTLIST

------------ ALL OBJECTS IN CLASS:
VFDCONTROL

VFDControl,
Plant Loop 1, !- Name
Motor, !- VFD Control Type
Motor, !- Pump rpm Schedule
Motor, !- Minimum Pressure
Schedule [Pa]
, !- Maximum Pressure
Schedule [Pa]
, !- Minimum RPM Schedule
, !- Maximum RPM Schedule
, !- Zone Name
Fraction
PowerPerFlowPerPressure, !- Design Power
Sizing Method
348701.1, !- Design Electric
Power per Unit Flow Rate (W/(m3/s))
1.282051282, !- Design Shaft Power
per Unit Flow Rate per Unit Head (W/(m3/s) - Pa)
0, !- Design Minimum Flow
Rate Fraction

------------ ALL OBJECTS IN CLASS:
AVAILABILITYMANAGER

AvailabilityManager,
Plant Loop 1, !- Name
Node 89, !- Demand Side Inlet
Node Name
Node 91, !- Demand Side Outlet
Node Name
Plant Loop 1 Demand Branches, !- Demand Side
Branch List Name
Plant Loop 1 Demand Connector List, !- Demand
Side Connector List Name
Optimal,
!- Load Distribution
Scheme
, !- Availability Manager
List Name
SingleSetpoint;
Calculation Scheme

------------ ALL OBJECTS IN CLASS:
PLANTEQUIPMENTLIST

------------ ALL OBJECTS IN CLASS:
VFDCONTROL

VFDControl,
Plant Loop 1, !- Name
Motor, !- VFD Control Type
Motor, !- Pump rpm Schedule
Motor, !- Minimum Pressure
Schedule [Pa]
, !- Maximum Pressure
Schedule [Pa]
, !- Minimum RPM Schedule
, !- Maximum RPM Schedule
, !- Zone Name
Fraction
PowerPerFlowPerPressure, !- Design Power
Sizing Method
348701.1, !- Design Electric
Power per Unit Flow Rate (W/(m3/s))
1.282051282, !- Design Shaft Power
per Unit Flow Rate per Unit Head (W/(m3/s) - Pa)
0, !- Design Minimum Flow
Rate Fraction

------------ ALL OBJECTS IN CLASS:
AVAILABILITYMANAGER

AvailabilityManager,
Plant Loop 1, !- Name
Node 89, !- Demand Side Inlet
Node Name
Node 91, !- Demand Side Outlet
Node Name
Plant Loop 1 Demand Branches, !- Demand Side
Branch List Name
Plant Loop 1 Demand Connector List, !- Demand
Side Connector List Name
Optimal,
!- Load Distribution
Scheme
, !- Availability Manager
List Name
SingleSetpoint;
Calculation Scheme

------------ ALL OBJECTS IN CLASS:
PLANTEQUIPMENTLIST

------------ ALL OBJECTS IN CLASS:
VFDCONTROL

VFDControl,
Plant Loop 1, !- Name
Motor, !- VFD Control Type
Motor, !- Pump rpm Schedule
Motor, !- Minimum Pressure
Schedule [Pa]
, !- Maximum Pressure
Schedule [Pa]
, !- Minimum RPM Schedule
, !- Maximum RPM Schedule
, !- Zone Name
Fraction
PowerPerFlowPerPressure, !- Design Power
Sizing Method
348701.1, !- Design Electric
Power per Unit Flow Rate (W/(m3/s))
1.282051282, !- Design Shaft Power
per Unit Flow Rate per Unit Head (W/(m3/s) - Pa)
0, !- Design Minimum Flow
Rate Fraction

------------ ALL OBJECTS IN CLASS:
AVAILABILITYMANAGER

AvailabilityManager,
Plant Loop 1, !- Name
Node 89, !- Demand Side Inlet
Node Name
Node 91, !- Demand Side Outlet
Node Name
Plant Loop 1 Demand Branches, !- Demand Side
Branch List Name
Plant Loop 1 Demand Connector List, !- Demand
Side Connector List Name
Optimal,
!- Load Distribution
Scheme
, !- Availability Manager
List Name
SingleSetpoint;
Calculation Scheme

------------ ALL OBJECTS IN CLASS:
PLANTEQUIPMENTLIST

------------ ALL OBJECTS IN CLASS:
VFDCONTROL

VFDControl,
Appendix G. EnergyPlus textfile sample

Cogeneration:DistrictHeating, !- Variable or Meter 13 Name
SumOrAverage; !- Aggregation Type for Variable or Meter 13

!- =========== ALL OBJECTS IN CLASS: OUTPUTCONTROL:TABLE:STYLE ===========
OutputControl:Table:Style,
    CommaAndHTML, !- Column Separator
    JtoKWH; !- Unit Conversion

!- =========== ALL OBJECTS IN CLASS: OUTPUTCONTROL:REPORTINGTOLERANCES ===========
OutputControl:ReportingTolerances,
    0.2, !- Tolerance for Time Heating Setpoint Not Met (deltaC)
    0.2; !- Tolerance for Time Cooling Setpoint Not Met (deltaC)

!- =========== ALL OBJECTS IN CLASS: OUTPUT:VARIABLE ===========
Output:Variable,
    *, !- Key Value Zone Air Temperature, !- Variable Name Hourly; !- Reporting Frequency

Output:Variable,
    *, !- Key Value Zone CO2 concentration !- Variable Name Hourly; !- Reporting Frequency